Driving Performance and Commuting Via an Automated Highway System

PUBLICATION NO. FHWA-RD-96-185

PB98-135056

JANUARY 1998

U.S. Department of Transportation
Federal Highway Administration

Research and Development
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, VA 22101-2296

FOREWORD

This report presents the results of one in a series of 14 experiments that investigated driver performance in a generic Automated Highway System (AHS) configuration. The experimental research was conducted in an advanced driving simulator. Each of six drivers traveled under automated control "to work" each morning on Wednesday, Thursday, Friday, and Monday, and "from work" each afternoon on the same days. The drivers drove manually before and after traveling on the AHS in each session. The drivers' steering and speed performance were compared in various ways to determine whether traveling under automated control had any effects on subsequent manual driving, the time course of any effects, the persistence of any effects across days, and whether there were diurnal effects. In addition, other measures, such as minimum following distance and lane-change gap acceptance, were examined for other effects. After exposure to the AHS, there were changes in both steering and speed maintenance; however, it appears that these effects cannot be attributed to automated travel. There were indications that the minimum following distance and incursion gaps may both have been smaller after the driver had traveled under automated control, suggesting more aggressive driving. This report will be of interest to engineers and researchers involved in Intelligent Transportation Systems and other Advanced Highway Systems.

Sufficient copies of the report are being distributed to provide a minimum of two copies to each FHWA regional and division office, and five copies to each State Highway Agency. Direct distribution is being made to division offices.

A. George Ostensen, Director
Office of Safety and Traffic Operations
Research and Development

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PB98-135056

Technical Report Documentation Page

1. Report No. FHWA-RD-96-185	2.	3. Recipient's Catalog No.
4. Title and Subtitle DRIVING PERFORMANCE AND COMMUTING VIA AN AUTOMATED HIGHWAY SYSTEM		5. Report Date January 1998
		6. Performing Organization Code
7. Author(s) A. John R. Bloomfield A. Angela R. Grant B. Lee Levitan A. J. Marty Christensen A. Timothy L. Brown A. Tammie L. Cumming A. Stephen J. Reinach A. Ginger S. Watson		8. Performing Organization Report No.
		10. Work Unit No. (TRAIS) 3B4d
9. Performing Organization Name and Address A. The University of Iowa, Center for Computer-Aided Design, 208 Engineering Research Facility, Iowa City, IA 52242 B. Honeywell Technology Center, 3660 Technology Drive, Minneapolis, MN 554[illegible]		11. Contract or Grant No. DTFH61-92-C-00100
		13. Type of Report and Period Covered Working Paper 8/95 - 6/96
12. Sponsoring Agency Name and Address Office of Safety and Traffic Operations R&D Federal Highway Administration 6300 Georgetown Pike McLean, Virginia 22101-2296		14. Sponsoring Agency Code

15. Supplementary Notes
Contracting Officer's Technical Representative (COTR)—Elizabeth Alicandri, HSR-30

16. Abstract
The current experiment—part of a series exploring human factors issues related to the Automated Highway System (AHS)—investigated the effect of repeated travel for extended periods under automated control to and from the same destination at the same times of day. The experiment, conducted in the Iowa Driving Simulator, used a generic AHS configuration in which the left lane was reserved for automated vehicles. Unautomated vehicles traveled in the center and right lanes. The center lane was not a dedicated transition lane; there were no barriers between the automated and unautomated lanes. Six commuters—three males, three females—participated in the experiment. Two lane-keeping measures and four speed-control measures were used to compare driving performance data collected before and after the commuters traveled under automated control. Seven additional measures, including minimum following distance and lane-change gap acceptance, were also used.
Results: (1) Effect of Automated Travel. The steering instability, velocity instability, and number of velocity fluctuations all changed after the driver traveled in the automated lane; after exposure to the AHS, there was progressively less steering instability, more velocity fluctuations, and progressively less velocity instability. However, these effects are most likely to be practice effects. There were hints that the minimum following distance and incursion gaps may both be smaller after the driver had traveled under automated control. (2) Other Effects. When the minimum accepted gaps for lane changes and the minimum rejected gaps for lane incursions were examined, they were found to cluster in the region between 40 m (131 ft) and 60 m (197 ft), suggesting that the minimum gap acceptable for a lane change is in this region. When traveling at a speed of 88.6 km/h (55 mi/h), the midpoint of this range is equivalent to a 2.0-s gap.

17. Key Words automated highway system, human performance, driving simulation, traffic flow, automation, intelligent vehicles, human factors.	18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 100	22. Price

Form DOT F1700.7 (8-72) Reproduction of Completed Page Authorized.

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: Volumes greater than 1000 l shall be shown in m^3.				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised September 1993)

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SECTION 1. INTRODUCTION AND OVERVIEW

INTRODUCTION

Currently, a great deal of attention is being focused on the possibility of using advanced technologies to develop an Automated Highway System (AHS), which would allow hands-off/feet-off travel in one's own vehicle. Human factors issues related to potential implementation of an AHS are being explored in an ongoing two-stage program being conducted for the Federal Highway Administration (FHWA). In the first stage of the program, seven experiments were conducted in the Iowa Driving Simulator. In the second stage, seven additional experiments have been conducted. This report presents the results of the seventh of these stage II experiments.

Like all of the experiments conducted in stage I, the current experiment used an AHS configuration that, if implemented, would require little structural alteration to the current roadways. This configuration consists of a three-lane expressway in which the left-most lane is reserved for automated traffic that travels in strings of up to four vehicles, while the vehicles that remain under the control of their drivers travel in the center and right lanes. With this configuration, the center lane is also used by vehicles that are in the process of transitioning into or out of the automated lane—there is no dedicated transition lane to and from that lane. Also, there are no barriers between the automated and unautomated lanes.

The experiments conducted in stage I of the program investigated the following:

- The transfer of control from the AHS to the driver of the simulator vehicle as the vehicle left the automated lane (experiments 1 and 2).[1]
- The transfer of control from the driver to the AHS as the simulator vehicle entered the automated lane (experiments 3 and 4).[2,3]
- The acceptability to the driver of a vehicle in the automated lane of decreasing vehicle separations as a vehicle enters the automated lane ahead of the driver's vehicle (experiment 5).[4]
- The effectiveness of the driver when he/she was required to control the steering and/or speed when traveling through a segment of the expressway in which the capability of the AHS was reduced (experiment 6).[5]
- The effect on normal driving behavior of traveling under automated control for very brief periods of time (experiment 7).[6]

The first five stage II experiments were run together in a single combined experiment that investigated the following:

- The behavior of the driver during the time that his/her vehicle was traveling under automated control (experiment 1).
- The kind of information that the driver would want to have available when his/her vehicle was traveling under automated control (experiment 2).
- The effect on normal driving behavior of traveling under automated control for an extended period of time (experiment 3).
- The effect on normal driving behavior of gaps of different lengths between the driver's vehicle and the vehicle ahead, during travel under automated control (experiment 4).
- The effect on normal driving behavior of different methods of transferring control from the automated system to the driver (experiment 5).

Levitan and Bloomfield reported the results of the first two of these experiments.(7) The remaining three are described by Bloomfield, Levitan, Grant, Brown, and Hankey.(8)

This report describes the seventh experiment of the program—it determined the effect on driving behavior of commuting via the AHS.[1]

THE EFFECTS OF TRAVELING IN AN AUTOMATED HIGHWAY SYSTEM

Three previous studies in this series of experiments provide some information about the effect of traveling under automated control on subsequent driving behavior. In the first of these studies, Bloomfield, Buck, Carroll, Booth, Romano, McGehee, and North investigated the transfer of control from the AHS to the driver when the driver's vehicle was leaving the automated lane.(1) In that experiment, after traveling in the automated lane for 2 to 3 min, control of the simulator vehicle was transferred from the AHS to the driver while the vehicle was in the automated lane and still traveling at the designated AHS velocity. Once in control, the driver was responsible for moving the vehicle from the automated lane to the center lane. Bloomfield et al. found that the driver decelerated before moving the vehicle into the center lane: When the designated AHS velocity was 104.7 km/h (65 mi/h), before moving from the automated lane to the center lane, the

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[1] It should be noted that an AHS configuration was not used in the sixth stage II experiment. Instead, the effect on driving behavior of two intelligent vehicle systems—a *speed, steering, and gap control* system (SSGCS) and a *collision warning* system (CWS)—was determined when the driver was traveling under different visibility and traffic density conditions.(9)

driver decelerated until the speed of the vehicle was virtually the same as the 88.6-km/h (55-mi/h) speed limit in the unautomated lanes; however, when the designated AHS velocity was higher—either 128.8 km/h (80 mi/h) or 153.0 km/h (95 mi/h)—the driver did not decelerate to the speed limit while the vehicle was still in the automated lane, but instead changed lanes and entered the unautomated center lane at speeds of 104.4 km/h (64.9 mi/h) and 110.3 km/h (68.5 mi/h), respectively.

In a second study, Bloomfield, Christensen, and Carroll directly investigated the effects on driving performance of brief periods of travel under automated control.(6) They focused on the post-AHS driving performance after the driver had moved into the unautomated lanes, and after he/she had finished decelerating and had selected a cruising speed. The main difference in pre- and post-AHS driving performance was that in order to maintain a chosen velocity, before traveling in the AHS, the driver made more frequent, smaller velocity correctio · however, after traveling in the AHS, the driver made less frequent, larger velocity corrections—perhaps because of becoming less attentive to speed. It is possible that more prolonged travel under automated control might exacerbate this effect to the point where it becomes problematic.

In a third study (Bloomfield, Levitan, Grant, Brown, and Hankey), the driver traveled under automated control for at least 35 min.(8) When control of the vehicle was transferred back to the driver in that experiment, the AHS had already reduced the speed of the vehicle from the designated AHS velocity to the speed limit and completed the lane change from the automated lane to the center lane. Driving performance data were obtained both before and after 36 drivers had experienced traveling under automated control. The performance of these drivers was compared with that of 12 control-group drivers, each of whom was in the simulator vehicle for the same length of time as the drivers who experienced travel under automated control, and each of whom drove the simulator vehicle throughout the session. Bloomfield et al. found that there was less steering instability and less velocity instability, and that there were more velocity fluctuations after the drivers in their experimental groups had traveled under automated control for an extended period of time. However, since they also obtained similar changes in performance for the control-group drivers, Bloomfield et al. were not able to attribute the changes in performance to the experience of traveling under automated control.(8) There were, however, two variables for which there were performance changes that suggested that drivers who had experienced extended periods of automated travel may have driven differently after the experience—both the minimum following distance and the minimum incursion gaps decreased for the experimental-group drivers after they traveled under automated control.(8)

The current experiment carried the investigation of the effect on driving behavior of traveling under automated control still further, examining the effect of commuting via the AHS. Six commuters participated in this experiment, which determined the effect of repeatedly traveling for extended periods under automated control to and from the same destination at the same times of day. Each commuter traveled "to work" in the morning and then returned in the afternoon on three consecutive days—Wednesday, Thursday, and Friday. Then, on the Monday following the 2-day weekend break, the commuter again traveled to and from work. Each journey was divided into three sections: In the first section, the commuter controlled the simulator vehicle, driving for approximately 13.5 km (8.4 mi); in the second section, the vehicle traveled under the control of the AHS for approximately 44.7 km (27.7 mi); while in the third section, the commuter again controlled the vehicle, driving approximately 12.7 km (7.9 mi). During the time that the commuter's vehicle was in the automated lane, it traveled at a velocity of 104.7 km/h (65 mi/h)—16.1 km/h (10 mi/h) faster than the speed limit in the unautomated lanes. Also in this period, the gap between the commuter's car and the vehicle immediately ahead in the string of automated vehicles was 0.0625 s or 1.82 m (5.96 ft), which is much smaller than the following distance typically chosen by drivers under normal driving conditions. Driving performance data were collected in the simulator before and after the commuter's vehicle had traveled under automated control. These data were compared in order to determine whether the experience of commuting under automated control affected the commuter's normal driving behavior.

OBJECTIVES OF THIS EXPERIMENT

The objectives of this experiment were:

- To determine whether the driving behavior of the commuter is affected by repeated travel under automated control.
- To determine whether prior exposure to the AHS affects the subsequent driving performance of the commuter.
- To determine whether the time of day affects the driving behavior of the commuter.
- To determine whether the driving behavior of the commuter varies from day to day.

To achieve these objectives, driving performance data were obtained in the simulator before and after each commuter traveled under automated control for an extended period of time twice a day for 4 days. The analyses of these data focused on the following experimental questions:

- *Does traveling under automated control for a single, extended period of time have an immediate effect on the commuter's driving performance?*

- *If traveling under automated control for a single, extended period of time does affect the commuter's driving performance, what is the time course of that effect?*
- *Does repeated travel under automated control for extended periods of time on consecutive days have an effect on the commuter's driving performance?*
- *Does repeated travel under automated control for extended periods of time, when the exposures to the AHS are not on consecutive days, have an effect on the commuter's driving performance?*
- *If traveling under automated control does affect the commuter's driving performance in the period of time that he/she drives after regaining control of his/her vehicle, do the effects persist and reoccur when the commuter drives again (without additional exposure to automated travel)?*
- *Is the commuter's driving performance affected by the time of day—specifically, in the morning when the commuter drives to work, does his/her driving performance differ from his/her driving performance in the afternoon when he/she drives home from work?*
- *Does the commuter's driving performance vary from day to day?*

SECTION 2. METHOD

SUBJECTS

The following guidelines were used to select the six commuters for this experiment:

- The commuters had no licensing restrictions, other than wearing eyeglasses for vision correction during driving.
- The commuters did not require special driving devices—the simulator is not equipped for such devices.
- One driver was selected from each of the following age ranges: less than 25 years old, between the ages of 25 and 34, between the ages of 35 and 44, between the ages of 45 and 54, between the ages of 55 and 64, and between the ages of 65 and 74.
- Three of the six commuters were male and three were female.
- The commuters were medically screened to ensure good physical and mental condition.
- The commuters had not participated in previous AHS experiments.

The six commuters who took part in this experiment were volunteers recruited through the Iowa City and University of Iowa daily newspapers, and who met the above selection criteria.

THE IOWA DRIVING SIMULATOR

The Iowa Driving Simulator, located in the Center for Computer-Aided Design at the University of Iowa, Iowa City, is shown in figure 1.[9] The physical configuration of the simulator consists of a domed enclosure mounted on a hexapod motion platform. The hexapod motion system employs 1.5-m (60-in) stroke hydraulic actuators to induce six-degree-of-freedom motion cues to the commuter. The motion system is capable of inducing correlated motion up to 5 Hz, vibration noise up to 8 Hz, and accelerations exceeding 1.0 *g*.

In this experiment, a Ford Taurus sedan was mounted on the motion platform, and the simulator was controlled by a computer complex that included a Harris Nighthawk 5800 and an Evans and Sutherland ESIG 2000 Computer Image Generator (CIG). The Nighthawk was controlled by the ICON operating system; it was responsible for arbitrating subsystem scheduling and performing motion control, data collection operations, instrumentation, control loading, and audio cue control.[10] The Nighthawk also performed the multibody vehicle dynamics and complex scenario-control simulation.

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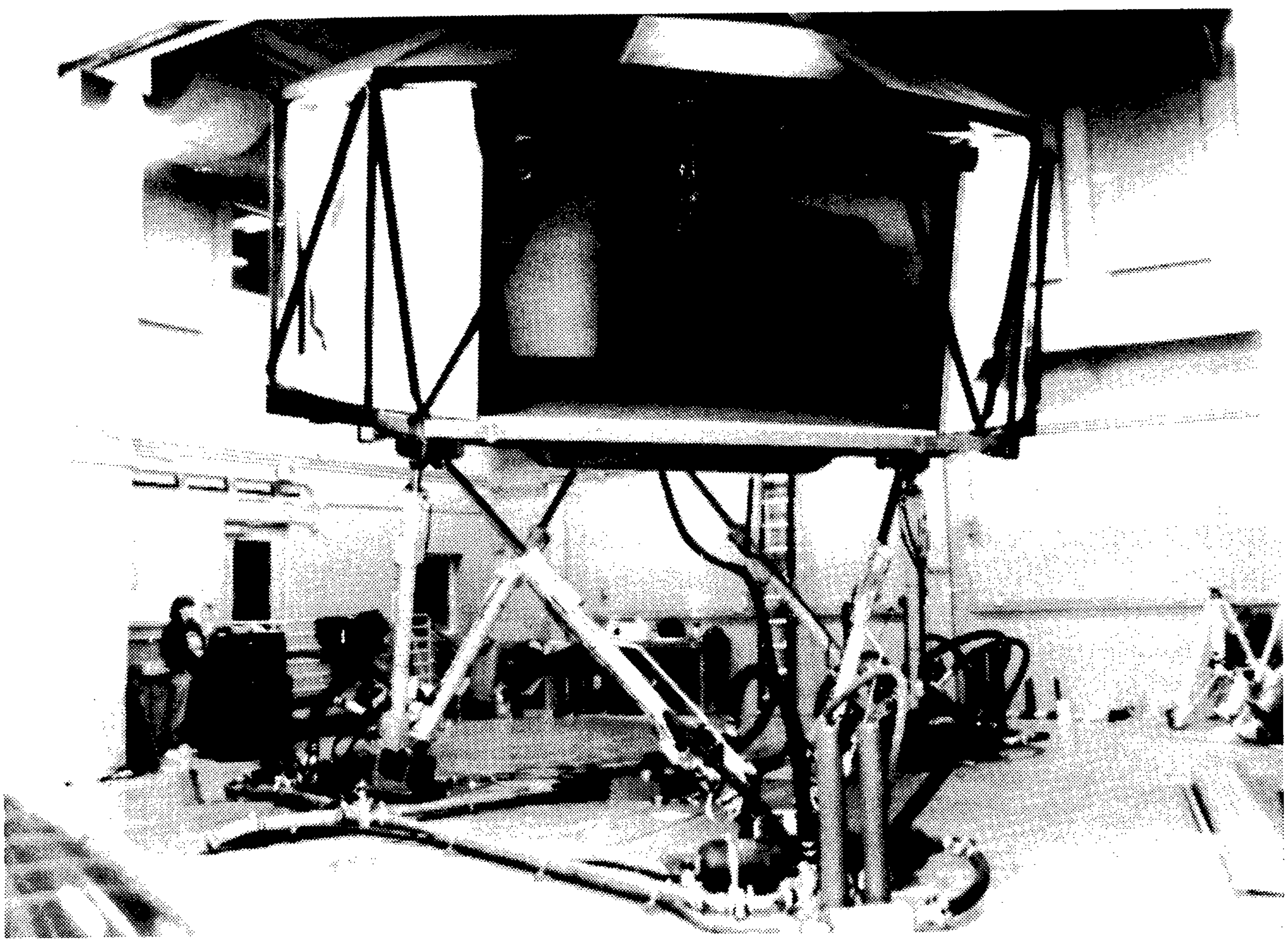

Figure 1. The Iowa Driving Simulator.

The inner walls of the dome act as a screen. For the current experiment, the correlated images generated by the CIG were projected onto two sections of these walls—one was a 3.32-rad (190°) section in front of the simulator vehicle, the other was a 1.13-rad (65°) section to its rear. The driver of the simulator vehicle viewed the images shown on the forward section through the windshield and side windows, and the images projected to the rear either by turning around, through an interior rearview mirror, or through a left-side exterior driving mirror.

DRIVING SITUATION

The driving situation for the commuter experiment can be described using the taxonomy of interactions between the driver and the AHS developed by Bloomfield, Buck, Carroll, Booth, Romano, McGehee, and North.[1] The experimental drives were conducted in dry weather conditions, with good visibility, on a three-lane expressway that was 96.6 km (60 mi) long—a map of this route is presented in appendix 2. The left lane was automated, the center and right lanes were unautomated, there was no transition lane, and there were no barriers between the automated and unautomated lanes. The lane widths were the current standard 3.66-m (12-ft) expressway width, and a standard road surface was used.

All of the automated vehicles involved in the experiment were directly controlled by the AHS. When the simulator vehicle was in the automated lane, the vehicle's steering wheel reflected the steering input from the AHS, the accelerator pedal reflected the vehicle behavior, and the brake pedal was disconnected.

The posted speed limit in the unautomated lanes was 88.6 km/h (55 mi/h). In the center and right lanes, the average velocity of the unautomated vehicles was fixed at 88.6 km/h (55 mi/h). The traffic density in the unautomated lanes was 12.42 v/km/ln (20 v/mi/ln)—this traffic density level, which is one at which traffic flows freely, is close to the upper boundary of the Transportation Research Board Level of Service B (LOS B).[11] With this traffic density, the mean headway time for vehicles in the unautomated lanes was 3.27 s. [Note: Mean headway time is the difference in arrival time of two consecutive vehicles at a particular observation point on the roadway. It includes both the length of the first vehicle and the gap between it and the following vehicle.] The distribution of the velocities of the unautomated vehicles was normal, while a Pearson Type III distribution was used to generate the time headways. The method used to generate vehicles in this experiment is described in detail by Bloomfield et al.[1] The parameters used in the equations defining both the normal distribution of velocities and the Pearson Type III distribution were derived using the procedure described by May and the data provided by May.(12,13)

Over the course of 4 days—three consecutive weekdays (Wednesday, Thursday, and Friday) and, after the 2-day weekend, the following Monday—each commuter participated in eight experimental sessions. There was a morning session in which the commuter traveled "to work," and an afternoon session in which he/she traveled back from work.

On Wednesday morning, the first day of the experiment, the commuter practiced driving in the simulator for 5 min. Then, as if going to work, the commuter traveled for 70.8 km (44 mi) on the expressway. The journey was divided into three sections. In the first section, the commuter controlled the simulator vehicle and drove in the right and center lanes of the expressway; 12.7 km (7.9 mi) after the start of the journey, the commuter received a message from the AHS and the transfer of control from the commuter to the AHS began. Approximately 13.5 km (8.4 mi) after the start of the journey, the second section of the journey began—the commuter's vehicle was in the automated left lane under the control of the AHS. This section lasted approximately 44.4 km (27.4 mi). Then, the AHS moved the vehicle back into the unautomated center lane and control was transferred back to the commuter. In the third section of the journey, the commuter again controlled the vehicle, driving approximately 12.7 km (7.9 mi) in the center and right lanes. To summarize, the journey was divided into three sections—a driver-controlled section before the AHS section, an AHS-controlled section, and a driver-controlled section after the AHS section. On Wednesday afternoon, the commuter drove or traveled in each section again, but in the reverse direction.

The morning commute to work and the afternoon return journey were repeated by each of the six commuters on the next 2 days and, after a 2-day weekend break, on the following Monday. Driving performance measures were collected from each commuter during the pre-AHS and post-AHS segments of the journey.

EXPERIMENTAL DESIGN

The six subjects who participated in the current experiment were balanced across age and gender, but no specific analyses were performed on either age or gender. The three independent variables that were explored all involved within-subjects comparisons. These variables are discussed below.

Pre-AHS vs. Post-AHS Driving Performance

The main focus of this experiment was on differences that might occur in driving performance measures collected before and after the commuters traveled under automated control. It was hypothesized that over a period of 4 days, the commuter might adapt to the AHS when his/her vehicle was under automated control for a large portion of the repeated journey, and that his/her normal driving performance might be affected. Samples of pre-AHS and post-AHS driving performance data were collected in the sections of driving immediately preceding and following the period of travel in the automated lane. During the pre-AHS and post-AHS portions of the trial, the commuter controlled the speed of the vehicle, decided whether to drive in the center or the right lane, and determined when to change lanes.

Diurnal Effects

An extensive body of research indicates that the efficiency of human performance in many areas is affected by circadian rhythms.(14) When the time of sampling is restricted to the normal waking part of the day, *diurnal rhythm* effects are found.(15) Monk, Fookson, Moline, and Pollak have shown that manual dexterity and horizontal scanning are among the areas of performance where diurnal effects are found.(16) Since these are behaviors utilized in driving, it is possible that there might be diurnal effects on driving performance, and that any such effects might be confounded with the effects on commuters of exposure to the AHS. Because of this, time of day was treated as an independent variable in the current experiment.

Day-to-Day Effects

Potentially, repeated exposure to the AHS could have an effect on driving performance. It is possible that such effects could be cumulative, although any cumulative effects that occur might be somewhat different when the 2-day weekend break intervenes between the Friday and Monday journeys. Day-to-day effects were investigated in the current experiment in order to explore these possibilities.

EXPERIMENTAL PROCEDURE

Introduction, Training, and Practice Procedure

Before beginning the experiment, each commuter watched a videotape containing introductory material describing this research program and the AHS, and had some interactive practice with the AHS interface and protocol. The commuter was told that the experiment involved driving the simulator for eight trials over the course of 4 days. The commuter was informed that this experiment was part of an ongoing FHWA program exploring ways of designing an AHS, and determining how it might work and how well drivers would handle their vehicles in such a system. It was made clear that the experiment was a test of the AHS, not a test of the driver. The video then gave explanations of the subtasks for the experiment—providing details to the commuter on how to:

- Transfer control of the vehicle to the AHS on entering the automated lane.
- Regain control back from the AHS on leaving the automated lane.

A narration of this training video is presented in appendix 1. The instructional section of the video lasted 9 min. When the video was presented to the commuters, the soundtrack was played at a volume that was pre-set to match the volume that would be heard in the simulator vehicle, and was not adjusted. Prior to presenting the training video, the commuter was asked to pay particular attention to the automated messages, as they would be exactly what would be heard in the vehicle. Then, after the training video was complete, he/she was asked:

> "Did you have any difficulty hearing any of those messages?"

This procedure was adopted to ensure that each commuter would be able to hear the messages when they were presented during the experimental trial.

After the instructional section of the video, the commuter performed a series of practice segments. The first of these segments contained subtask practice that dealt with transferring control to the AHS and then transferring control back from the AHS to the commuter. There were three practice segments for each of these subtasks. If the commuter responded correctly on the first two segments, the third was omitted. If the commuter did not respond correctly twice in a row for a particular subtask, the three segments were repeated until he/she was able to accomplish this. Following the subtask practices, the videos concluded with three more segments that covered the whole task—as before, if the commuter responded correctly on the first two trials, the third was omitted, and if more than three trials were required, the segments were repeated.

Pre-Experimental Simulator Procedure

At the beginning of each of the eight drives, the commuter was taken to the Iowa Driving Simulator and seated in the driver's seat of the simulator vehicle. He/she was asked to put on the seatbelt and adjust the seat and mirrors, and then was given instructions on how to use the simulator emergency button. The commuter was made aware that the headlights of the vehicle were already switched on, and that the air conditioner, dome lights, turn signal, and radio were operational. The commuter was told that if, for any reason, he/she wanted to stop at any time during the journey, to simply say so and the operator would stop the simulation. Instructions were then given on how to use the simulator emergency button. An experimenter was present in the back seat on the passenger's side of the simulator vehicle throughout all the experimental sessions.

On the first of the eight sessions, before beginning what would be the regular commute, there was a practice drive. This allowed the commuter to become familiar with the way that the simulator car handled by driving the vehicle on an expressway for 5 min.

Pre-AHS Experimental Procedure and Instructions

The commuter completed eight full journeys—traveling "to and from work" on 4 weekdays (Wednesday, Thursday, Friday, and the following Monday). During each of the eight journeys, the commuter traveled in the simulator vehicle for about 70.8 km (44 mi). At the beginning of the journey, the vehicle was parked on an expressway entrance ramp. The commuter drove the vehicle into the right lane and then drove in the right and center lanes for approximately 12.7 km (7.9 mi) before receiving instructions from the AHS. The density of the unautomated traffic in these two lanes was 12.4 v/ln/km (20 v/ln/m).

The commuter was informed that the left lane was reserved for automated vehicles, and that if he/she drove into it, the following auditory warning would be heard:

> "You've entered the left lane. You're not authorized to be in the left lane. Return to the center lane immediately."

After traveling for 12.7 km (7.9 mi) from the start of the trial, in order to prepare for entry into the AHS, the commuter received one of two auditory messages—one message was given if the vehicle was in the right lane, the other was given if it was in the center lane. If the vehicle was in the right lane, the message was as follows:

"Please move to the center lane and, when you get there, wait for further instructions."[1]

Then, as soon as the commuter moved to the center lane, the following message was presented:

"Please remain in the center lane and wait for further instructions."

If the commuter had not complied with this message within 10 s, it would have been repeated; if he/she had not complied with the message after three presentations, the following message would have been presented and the experiment would have been terminated:

"Please pull over to the right shoulder and stop."

If the commuter was already in the center lane 12.7 km (7.9 mi) from the start of the trial, the AHS issued the following message:

"Please remain in the center lane and wait for further instructions."

If the commuter had not complied, and had left the center lane, the following message would have been presented:

"Please move to the center lane and, when you get there, wait for further instructions."

If the commuter had not complied with this message within 10 s, it would have been repeated; if he/she had not complied with the message after three presentations, the following message would have been presented and the experiment would have been terminated:

"Please pull over to the right shoulder and stop."

When the commuter's vehicle was in the center lane, approximately 13.5 km (8.4 mi) from the start of the trial, the AHS presented the following message:

"To engage the automated system, push the *On* button now."

If the commuter complied by pressing the *On* button on the steering wheel, the following message was presented auditorily:

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[1] It should be noted that: (1) a tone preceded each presentation by the AHS of an auditory verbal message, and (2) whenever an auditory message was presented by the AHS, the vehicle's radio speaker was silenced during the entire time the message was being presented.

"Welcome to the Automated Highway System. Your vehicle is now controlled by the automated system. You will enter the automated lane in a moment."

If the commuter had not pressed the *On* button, the message would have been repeated at 5-s intervals up to two additional times. Throughout the pre-AHS portion of the trial, the simulator vehicle remained under the control of the commuter.

AHS Experience

As soon as the commuter pressed the *On* button, the AHS took full control of the simulator vehicle and drove it into the automated lane between two strings of automated vehicles. Once in the automated lane, the AHS increased the velocity of the vehicle until it caught up to the string ahead and became the last vehicle in that string.

While the vehicle was under automated control, the commuter was allowed to do whatever he/she wanted to do while remaining in the driver's seat. If the commuter had taken reading materials or anything else into the simulator vehicle to occupy his/her time, he/she could have used them during this section of the journey. A strip map of the route the commuter was traveling was also made available. Copies of the maps used in the morning and afternoon drives are presented in appendix 2. The vehicle traveled under automated control for approximately 44.7 km (27.7 mi).

Post-AHS Experimental Procedure and Instructions

Approximately 12.7 km (7.9 mi) from the exit at the end of the journey, in order to allow the commuter to prepare to regain control of the vehicle, the following message was presented:

"You will leave the automated lane in 30 seconds. Once in the center lane, you will be asked to resume control of your vehicle."

As it presented this message, the AHS began to reduce the speed of the simulator vehicle. It continued to control the vehicle, reduced its speed to 88.6 km/h (55 mi/h), and then moved it into the center lane. Then, the AHS issued the following message:

"To regain control of the vehicle, put your hands on the steering wheel and press the accelerator or brake pedal."

As soon as the commuter pressed the accelerator or the brake pedal while holding the steering wheel, the AHS relinquished control of the vehicle and issued the following message:

> "You now have complete control of your vehicle."

The commuter was in control of the vehicle for the rest of the journey. As the commuter approached the end of the drive to work, the following message was presented:

> "In 30 seconds you will reach your destination. You should move into the right lane and leave the freeway at the next exit."

On hearing this message, the commuter prepared to leave the expressway—moving into the right lane if in the center lane when the message was issued, or staying in the right lane if already in it. Then, the commuter drove off the expressway onto the designated exit ramp.

Post-Experimental Procedure

After the first session on Wednesday morning, the commuter returned to the subject preparation room, where he/she was asked to complete a questionnaire that contained questions dealing with the driving simulator, the commuter's experience in the simulator vehicle, and the Automated Highway System. A copy of the questionnaire is presented in appendix 3.

The commuter also went to the subject preparation room after the last session on Monday afternoon. This time, after being asked to complete the questionnaire again, the commuter was debriefed.

SECTION 3. RESULTS

FOCUS OF THE DATA ANALYSIS

The objectives of this experiment were: (1) to determine whether the driving behavior of the commuter is affected by repeated travel under automated control, (2) to determine whether prior exposure to the AHS affects the subsequent driving performance of the commuter, (3) to determine whether the time of day affects the driving behavior of the commuter, and (4) to determine whether the driving behavior of the commuter varies from day to day. The analyses of these data focused on the following specific experimental questions:

- *Does traveling under automated control for a single, extended period of time have an immediate effect on the commuter's driving performance?*
- *If traveling under automated control for a single, extended period of time does affect the commuter's driving performance, what is the time course of that effect?*
- *Does repeated travel under automated control for extended periods of time on consecutive days have an effect on the commuter's driving performance?*
- *Does repeated travel under automated control for extended periods of time, when the exposures to the AHS are not on consecutive days, have an effect on the commuter's driving performance?*
- *If traveling under automated control does affect the commuter's driving performance in the period of time that he/she drives after regaining control of his/her vehicle, do the effects persist and reoccur when the commuter drives again (without additional exposure to automated travel)?*
- *Is the commuter's driving performance affected by the time of day—specifically, in the morning when the commuter drives to work, does his/her driving performance differ from his/her driving performance in the afternoon when he/she drives home from work?*
- *Does the commuter's driving performance vary from day to day?*

DRIVING PERFORMANCE MEASURES

In order to answer these questions, driving performance data were obtained from six commuters as they traveled on a simulated journey to and from work on 4 weekdays spread out over a 6-day period. Each commuter drove on 3 consecutive days, took a 2-day weekend break, and then drove again on the first day of the next week. Each journey was 70.8 km (44.0 mi) long, lasted for approximately 45 min, and was divided into three sections (pre-AHS, AHS, and post-AHS).

In the pre-AHS section, driving performance data were collected from the time that the vehicle entered the expressway until the time that the AHS issued a message requesting the commuter to move to, or to stay in, the center lane. The message was issued after the commuter had traveled 12.7 km (7.9 mi)—approximately 8.5 min if the commuter drove at the speed limit throughout the pre-AHS section.

In the AHS section of the journey, the vehicle traveled 44.7 km (27.7 mi) at 104.7 km/h (65 mi/h) while it was in the automated lane under the control of the AHS.

Then, in the post-AHS section, driving performance data were collected from the time that complete control of the vehicle had been transferred back to the commuter until he/she reached the designated exit. The transfer of control began when there were approximately 12.7 km (7.9 mi) of the journey left. Since the transfer of control took approximately 60 s, if the commuter drove at the speed limit throughout the post-AHS section, he/she would have driven for approximately 7.5 min.

During the pre-AHS and post-AHS sections of the journey, 13 driving measures were collected. These measures are listed in table 1.

In order to determine the time course of any effects that traveling under automated control might have had on driving performance, the post-AHS section of the journey was divided into seven 1-min segments. Since the commuter actually drove for approximately 7.5 min in the pre-AHS section of the drive, with this segmentation scheme, approximately 30 s of data were not used. The segmentation scheme was appropriate for the first six driving measures listed in table 1. The six measures for which this segmentation was possible were the two lane-keeping measures (steering instability and steering oscillations) and the four speed-control measures (average velocity, velocity drift, velocity instability, and velocity fluctuations).

Five of the six driving measures for which the segmentation scheme was appropriate were developed recently. Bloomfield and Carroll suggest that teh driver's lane-keeping performance can be described in terms of a linear equation that is the line of best fit for a series of points along the track of a vehicle.[17] This equation describes the position of a vehicle relative to the center of the lane at any time. The two lane-keeping measures listed in table 1 are measures of the driver's

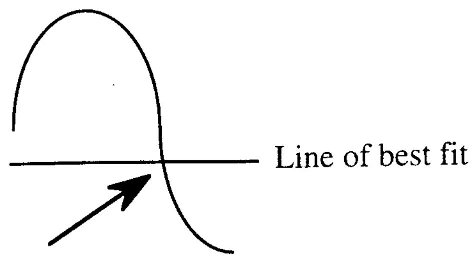
Table 1. Driving performance measures collected in the pre-AHS and post-AHS sections of the commuter's journey to and from work.

Lane-keeping measures
Steering instability[1]
Number of steering oscillations[1]
Speed-control measures
Average velocity
Velocity drift[1]
Velocity instability[1]
Number of velocity fluctuations[1]
Following-distance measure
Minimum following distance
Lane-change measures
Percent of time spent in the center lane
Percent of time spent in the right lane
Number of lane changes
Size of gap accepted in each lane change
Incursion measures
Number of incursions
Size of gap rejected in each lane incursion

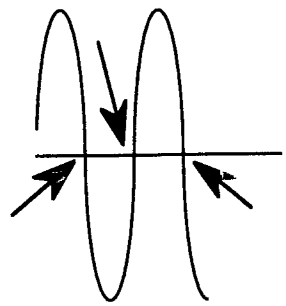
[1] Driving performance measures developed by Bloomfield and Carroll.(17) A brief account describing the development of these measures is provided in ppendix 4.

steering ability that are derived from this equation. The steering instability is a measure of the variability of the track of the vehicle around the line of best fit, while the number of steering oscillations indicates the number of crossings of the line of best fit per minute (figure 2 illustrates these concepts).

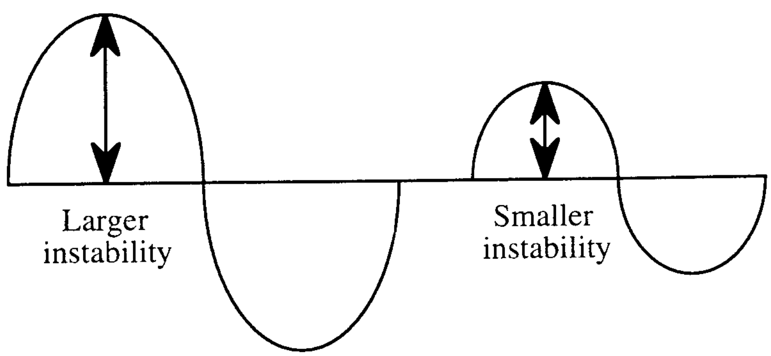
Bloomfield and Carroll also suggest that the driver's ability to control the speed of his/her vehicle can be described using another linear equation that is the line of best fit for speed control.(17) Three of the four speed control measures listed in table 1 are derived from this equation. The velocity drift can be used to indicate if the driver is increasing or decreasing the speed of the vehicle. Velocity instability is a measure of the variability around the velocity maintenance line of



(a)



(b)



(c)

Figure 2. Illustrations of: (a) one steering oscillation, (b) three steering oscillations, and (c) two levels of steering instability.

best fit, and the number of velocity fluctuations is the number of times per minute that the velocity of the vehicle crosses the velocity maintenance line. Figure 2 above illustrates that velocity **fluctuations** are conceptually the same as steering **oscillations**; instability is functionally the same for both velocity and steering. [Further details of the derivation of these measures are presented in appendix 4.]

Average velocity, the remaining speed-control measure in table 1, will give an overall indication of the driver's speed.

The following-distance measure, the four lane-change measures, and the two incursion measures that are listed in table 1 are self-explanatory. It is not appropriate to use the segmentation scheme with the minimum following distance[1], the percentage of time spent in the right lane and in the center lane, the number of lane changes, the size of the gap accepted in each lane change, the number of lane incursions, and the size of the gap rejected in each lane incursion.

DATA ANALYSIS APPROACH

The experiments conducted in stage I of this program can be characterized as "What if . . . ?" experiments—the type of question asked in them was "Which differences are significant?" The appropriate statistical approach in analyzing the data obtained in those experiments was to conduct what Tukey calls exploratory data analysis.(18) With this approach, the data are analyzed with analyses of variance (ANOVA's); then, any significant effects uncovered by the ANOVA's are examined with post hoc tests. As Winer, Brown, and Michels have pointed out, post hoc tests are used when the statistical tests are related to the structure of the outcome of the initial ANOVA.(19)

In contrast, the experimental questions asked in the current experiment are far more specific than those asked in the first stage of the program—the type of question asked here is "Is this difference significant?" Because of the change in the type of question asked, i.e., because of the change from exploratory data analysis to confirmatory data analysis, it is necessary to use a different statistical approach in analyzing the data.(18) With confirmatory data analysis—which is conducted by means of a priori, or planned, comparisons—the statistical tests are related to the structure of the obtained data, rather than to the structure of the outcome.(19) When data are analyzed using planned comparisons, Keppel argues that as long as the number of comparisons is kept lower than the number of degrees of freedom associated with the treatment source of variances, there is no need to modify the error term.(20) However, in this experiment, where the number of comparisons was sometimes lower and at other times higher than the number of degrees of freedom associated with the treatment sources of variance, a more conservative approach was adopted—the error term was modified to account for the number of comparisons

[1] The minimum following distance was the smallest distance between the front bumper of the driver's car and the back bumper of the vehicle ahead that was maintained for at least 10 s. A detailed description of how the following distance data were collected is presented later in this report when the analysis of these data is discussed.

being conducted. The following three a priori tests were used, as appropriate, with the first six driving performance measures:

- The Dunnett procedure was used to determine the effect on driving performance of exposure to the AHS.(21)
- The Tukey Studentized range test, with the Tukey-Kramer modification, was used to determine whether there were any AHS carryover effects and whether there was a day-to-day effect.(22-24)
- The Dunn-Bonferroni procedure was used to determine whether there were any diurnal effects.(25)

In addition, the t-test and the chi-square statistic were used to analyze the data obtained with the seven driving performance measures for which segmentation was not appropriate, and to analyze the responses to the questionnaire.

AHS EFFECTS

In order to determine whether the driving performance of the commuter was affected by traveling in the automated lane, the Dunnett procedure was used a priori to answer the following questions:(21)

- *Does traveling under automated control for a single, extended period of time have an immediate effect on the commuter's driving performance?*
- *If traveling under automated control for a single, extended period of time does affect the commuter's driving performance, what is the time course of that effect?*

To determine whether traveling under automated control for an extended period of time had an immediate effect on the commuter's driving performance, the pre-AHS driving performance measures obtained during the period when the commuter drove in the morning on Wednesday, the first day of the experiment, were compared with the driving performance data obtained in the first 1-min segment of the post-AHS section of the Wednesday morning commute. Then, to determine the time course of such effects, the same pre-AHS driving performance data were compared with the driving performance data obtained in the second, third, fourth, fifth, sixth, and seventh consecutive 1-min segments of the post-AHS section of the Wednesday morning commute. The results of these comparisons are presented in table 2, and are discussed in the following subsections of the report.

Table 2. Result of using the Dunnett procedure to determine whether traveling under automated control for an extended period of time had either an immediate or a prolonged effect. [This was accomplished by comparing driving performance data obtained in the pre-AHS section of the Wednesday morning journey with similar data obtained in the first, second, third, fourth, fifth, sixth, and seventh 1-min segments of the post-AHS section of the Wednesday morning journey.][1]

	Wednesday a.m. post-AHS segment						
Driving Performance Measure	1	2	3	4	5	6	7
Steering instability	*	*	*	*	*	*	*
Steering oscillations	–	–	–	–	–	–	–
Average velocity	–	–	–	–	–	–	–
Velocity drift	–	–	–	–	–	–	–
Velocity instability	*	*	*	*	*	*	*
Velocity fluctuations	*	–	–	–	–	*	–

[1] An asterisk indicates that the difference between the a.m. pre-AHS data and the a.m. post-AHS data indicated by the columns was statistically significant at the $p < 0.05$ level for the driving measure indicated by the rows.

The Immediate Effect of Traveling Under Automated Control

As the first column of table 2 shows the Dunnett procedure revealed that traveling under automated control did have a statistically significant immediate effect on three of the driving performance measures—steering instability, velocity instability, and velocity fluctuations. These effects are shown in figures 3, 4, and 5.

Figure 3 shows the immediate effect of traveling in the AHS on steering instability. The commuters had an average steering instability of 0.44 m (1.4 ft) during the pre-AHS section of their first journey on Wednesday morning, before experiencing the automated system. This dropped to 0.26 m (0.9 ft) in the first post-AHS 1-min period.

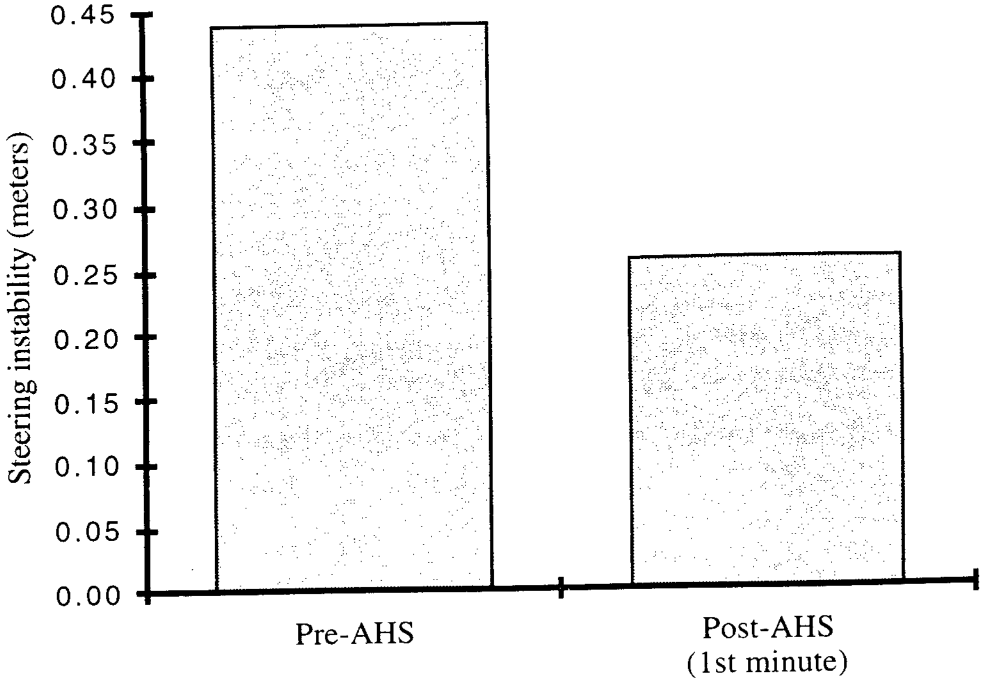


Figure 3. Steering instability for the pre-AHS section and for the first minute of the post-AHS section of the Wednesday morning journey.

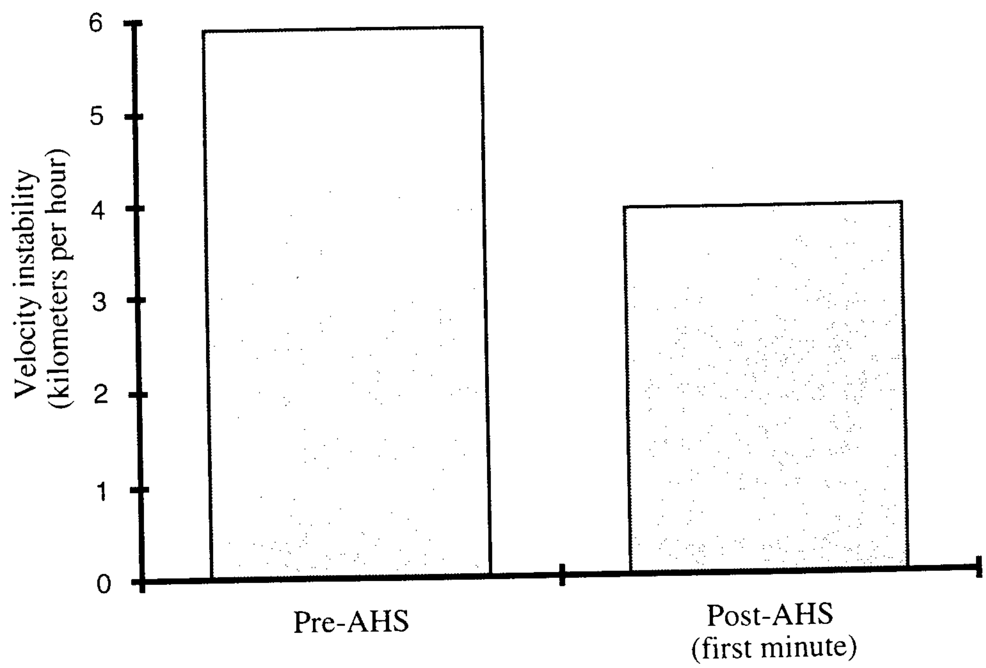


Figure 4. Velocity instability for the pre-AHS section and for the first minute of the post-AHS section of the Wednesday morning journey.

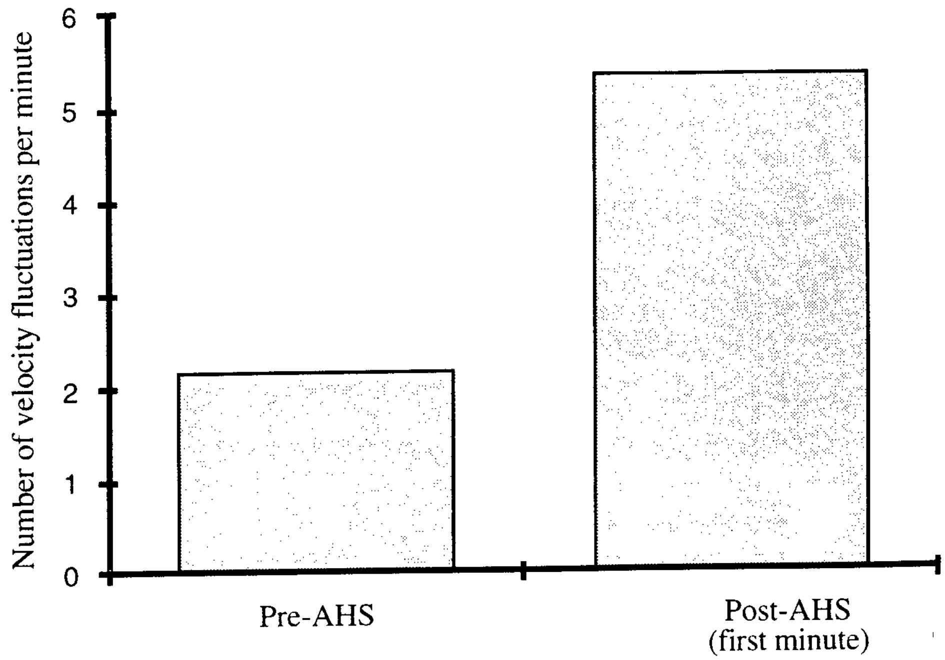


Figure 5. Number of velocity fluctuations per minute for the pre-AHS section and for the first minute of the post-AHS section of the Wednesday morning journey.

Figure 4 shows a similar effect for velocity instability—it dropped from an average of 5.90 km/h (3.66 mi/h) for the pre-AHS section of the first journey on Wednesday morning to 3.94 km/h (2.44 mi/h) in the first minute after experiencing the AHS.

Finally, as figure 5 shows, the number of velocity fluctuations increased from an average of 2.17 fluctuations per minute in the pre-AHS section of the Wednesday morning journey to 5.33 fluctuations per minute in the first minute after leaving the automated lane.

It should be noted that all three of these changes in performance—the decrease in the steering instability, the decrease in the velocity instability, and the increase in the number of velocity fluctuations—should be considered improvements in driving performance. While it is obvious that reductions in steering instability and velocity instability will result in smoother driving, it is perhaps less obvious why the increase in the number of velocity fluctuations should be considered an improvement. However, the increase in the number of velocity fluctuations per minute that occurred in this experiment concurrently with the decrease in velocity instability could happen only if the driver was exerting finer control over the speed and making many more small adjustments in speed, i.e., the driver reduced the velocity instability, keeping closer to the line of best fit by crossing that line more frequently.

The Prolonged Effect of Traveling Under Automated Control

The Dunnett procedure was also used to determine the time course of the effect on driving performance of traveling under automated control for an extended period of time—would the immediate effects be prolonged beyond the first post-AHS 1-min period to the seventh minute? Driving performance measures collected on Wednesday morning before the commuter experienced the AHS were compared to those same measures collected for the second, third, fourth, fifth, sixth, and seventh consecutive post-AHS minutes. The immediate effects of traveling under automated control on the two instability measures were found to be prolonged until the seventh minute of the post-AHS section of the journey. The steering instability and the velocity instability measures were both found to be significantly smaller in all seven 1-min post-AHS periods compared to the pre-AHS period. These two effects can be seen in figures 6 and 7.

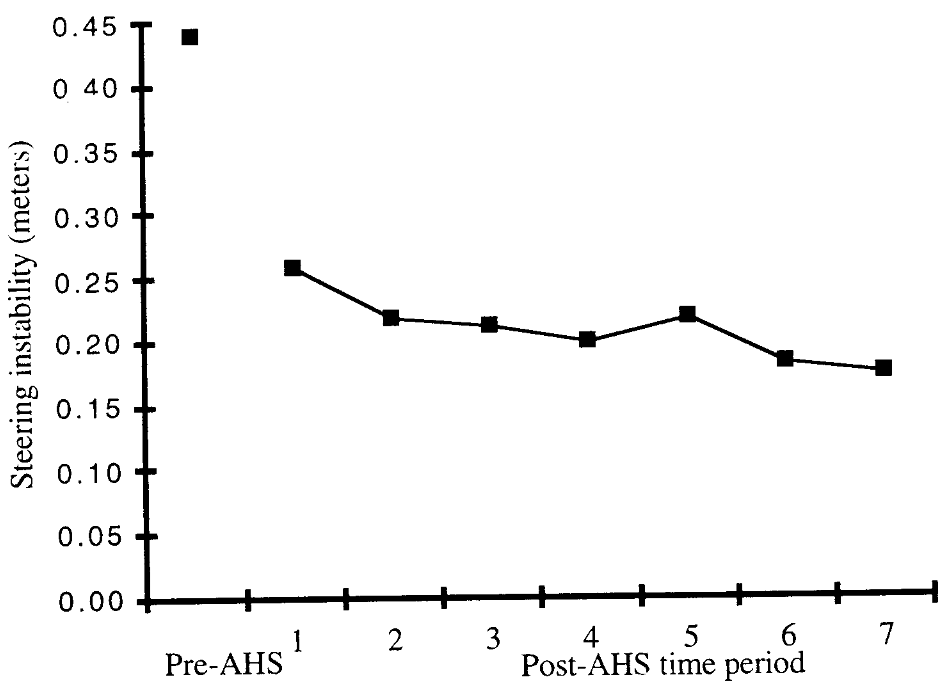


Figure 6. Steering instability for the Wednesday morning journey.

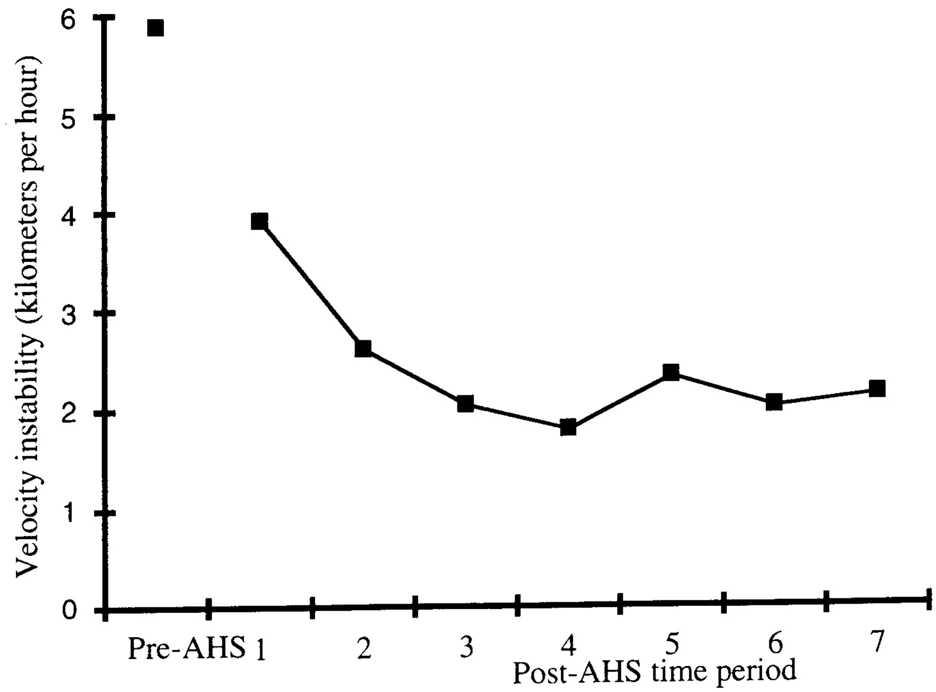


Figure 7. Velocity instability for the Wednesday morning journey.

Figure 6 shows that the average steering instability in the second, third, fourth, fifth, sixth, and seventh post-AHS 1-min periods was approximately 50 percent lower than it was before the commuter traveled in the automated lane. Similarly, figure 7 shows that the velocity instability dropped approximately 60 percent after the commuter had experienced traveling under automated control.

There was also an indication that the immediate effects of traveling under automated control on the number of velocity fluctuations might also be prolonged—although the effect was not clear-cut with this measure. Over the last six 1-min segments of post-AHS driving, the number of velocity fluctuations was only significantly different from the pre-AHS section of the journey in one segment (number six). The variation in the number of velocity fluctuations per minute throughout the post-AHS section of the Wednesday morning journey is shown in figure 8.

The Dunnett procedure was also used to determine whether any of the driving performance measures that were not immediately affected by the AHS were significantly different in the second,

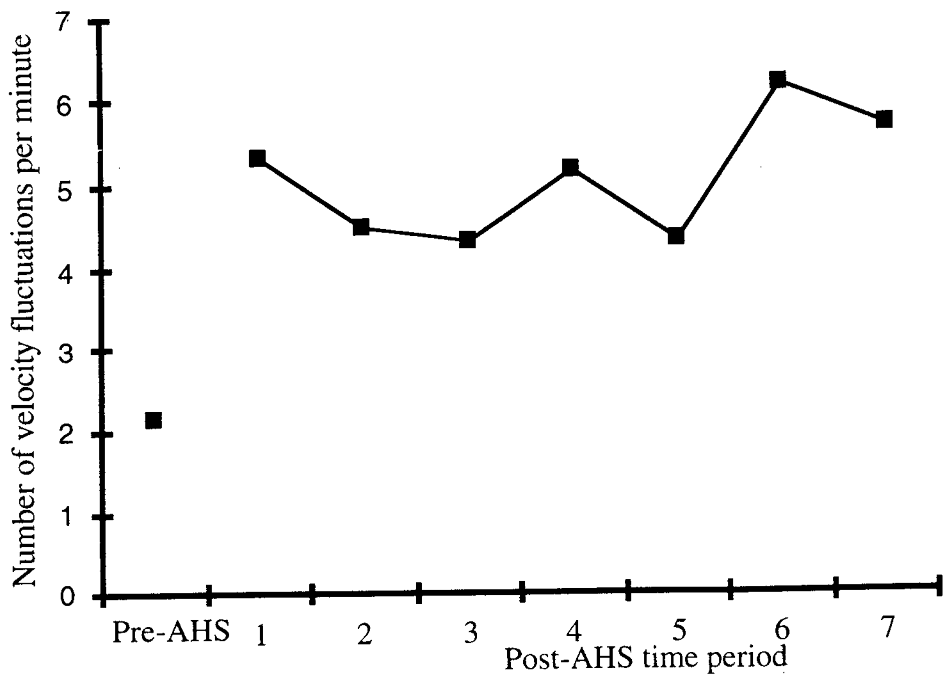


Figure 8. Number of velocity fluctuations for the Wednesday morning journey.

third, fourth, fifth, sixth, or seventh post-AHS 1-min periods during the Wednesday morning drive. As can be seen from table 2, no other significant effects of travel in the automated system on the remaining measures emerged in the remainder of the post-AHS drive.

The Effect of Repeatedly Traveling Under Automated Control

To determine whether the driving performance of the commuter was affected by repeated travel in the automated lane, the following questions were addressed:

- *Does repeated travel under automated control for extended periods of time on consecutive days have an effect on the commuter's driving performance?*
- *Does repeated travel under automated control for extended periods of time, when the exposures to the AHS are not on consecutive days, have an effect on the commuter's driving performance?*

The a priori comparisons that were to be used to determine the answers to these questions were conditional—they depended on the results of the tests conducted to see if the commuter's driving performance was affected by the time of day. As will be reported later, the time of day did affect the driving performance measures.

If no diurnal effects had been found, the effect on driving performance of repeated travel on consecutive days would have been tested by comparing the pre-AHS driving performance obtained on Wednesday morning, before the commuter experienced travel under automated control, with the post-AHS driving performance obtained on Friday afternoon. In addition, the effect on driving performance of repeated travel when the exposures were not on consecutive days would have been tested by comparing the pre-AHS driving performance obtained on Wednesday morning with the post-AHS driving performance obtained on Monday afternoon. However, since statistically significant diurnal effects were found, the effect on driving performance of repeated travel on consecutive and nonconsecutive days was instead explored by comparing the pre-AHS driving performance obtained on Wednesday morning with the post-AHS driving performance obtained on Friday and Monday mornings, respectively.

The Dunnett procedure was used to determine whether repeated travel under automated control had an effect when it was experienced on consecutive days—the driving performance measures collected on Wednesday morning before the commuter had any exposure to the automated system were compared to the seven 1-min periods in the post-AHS segment on Friday morning, the third consecutive day of commuting. And, in order to determine whether repeated travel under automated control had an effect when the exposures to the AHS were not on consecutive days, the driving performance measures collected pre-AHS on Wednesday morning were compared to the seven 1-min periods in the post-AHS segment on Monday morning. The results of these comparisons are shown in table 3.

As table 3 shows, the three measures that were affected after the commuter had traveled only once under automated control for an extended period—steering instability, velocity instability, and velocity fluctuations—were also affected in the post-AHS section of the journey on both Friday and Monday mornings. These effects are shown in figures 9, 10, and 11.

The effect on steering instability of repeated exposure to the AHS is illustrated in figure 9. When the steering instabilities obtained in each of the seven 1-min post-AHS periods of time on Friday morning, after exposure to the AHS on three consecutive days, i.e., after five consecutive journeys—two each on Wednesday and Thursday, and one pre-AHS on Friday morning—were compared to the first pre-AHS drive on Wednesday, the steering instability was found to have decreased by at least 43 percent. When a similar comparison was made using the data obtained on

Table 3. Results of using the Dunnett procedure to determine whether repeated travel under automated control for extended periods of time on consecutive and nonconsecutive days had an effect. [This was accomplished by comparing driving performance data obtained in the pre-AHS section of the Wednesday morning journey with similar data obtained in the first, second, third, fourth, fifth, sixth, and seventh 1-min segments of the post-AHS section of the Friday and Monday morning journeys.][1]

	Friday a.m. post-AHS segment							**Monday a.m. post-AHS segment**						
Driving Performance Measure	1	2	3	4	5	6	7	1	2	3	4	5	6	7
Steering instability	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Steering oscillations	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Average velocity	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Velocity drift	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Velocity instability	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Velocity fluctuations	–	*	–	–	*	*	–	–	–	–	–	*	–	*

[1] An asterisk indicates that the difference between the Wednesday a.m. pre-AHS data and the Friday and Monday a.m. post-AHS data indicated by the columns was statistically significant at the $p < 0.05$ level for the driving measure indicated by the rows.

Monday morning, after the commuter had been exposed to the AHS on seven occasions, but on nonconsecutive days, the steering instability was found to have still decreased by at least 40 percent.

Similar comparisons were conducted for the velocity instability measure, as figure 10 shows. The velocity instability decreased by at least 42 percent from the first pre-AHS drive on Wednesday to the seven post-AHS periods on Friday morning. And it had decreased by at least 47 percent for the seven post-AHS periods on Monday morning.

The change in the number of velocity fluctuations per minute throughout the experiment is shown in figure 11. As table 3 indicates, the number of velocity fluctuations per minute was found to be significantly higher on Friday morning during the second, fifth, and sixth minutes of post-AHS driving, and on Monday morning during the fifth and seventh minutes of post-AHS driving, than the number obtained during the first pre-AHS section on Wednesday. (Although it

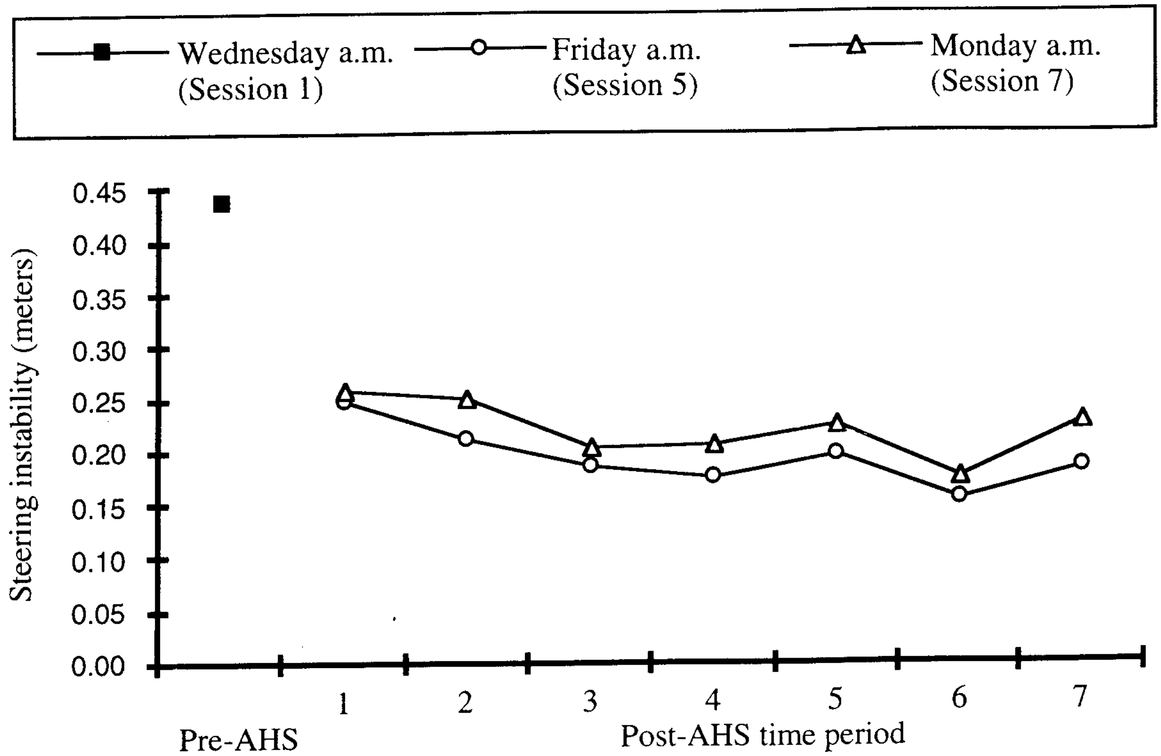


Figure 9. Steering instability for the pre-AHS section of the Wednesday morning journey and for the post-AHS section of the Friday and Monday morning journeys.

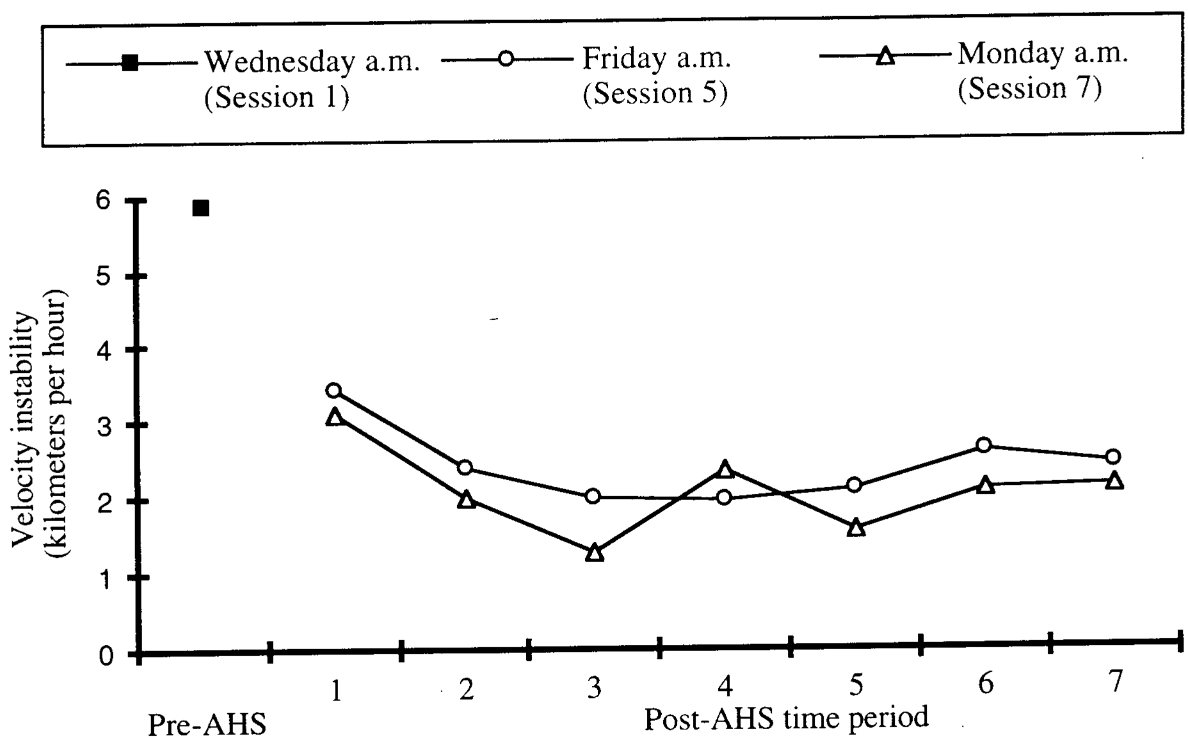


Figure 10. Velocity instability for the pre-AHS section of the Wednesday morning journey and for the post-AHS section of the Friday and Monday morning journeys.

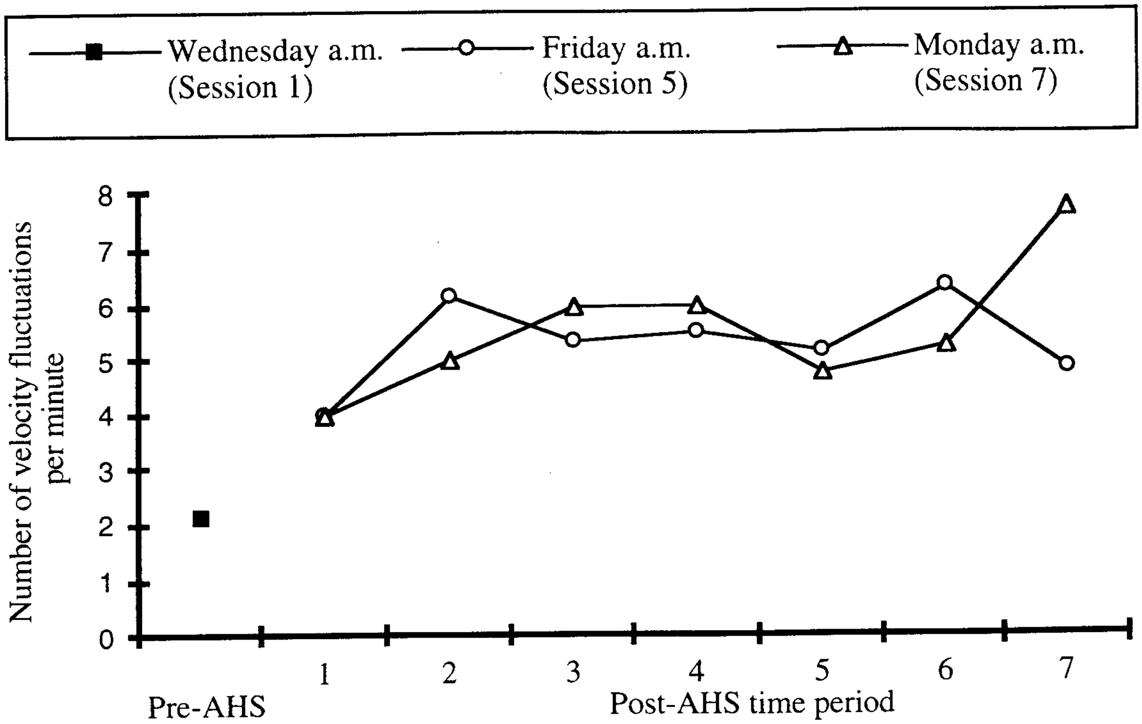


Figure 11. Number of velocity fluctuations per minute for the pre-AHS section of the Wednesday morning journey and for the first, second, third, fourth, fifth, sixth, and seventh minutes of the post-AHS section of the Friday and Monday morning journeys.

appears in figure 11 that other differences should also be significant, they, in fact, are not, due to differences in error terms for the various comparisons.)

The Persistence of the Effect of Traveling Under Automated Control

The specific experimental question related to the persistence of the effects of traveling under automated control was as follows: *If traveling under automated control does affect the commuter's driving performance in the period of time that he/she drives after regaining control of his/her vehicle, do the effects persist and reoccur when the commuter drives again (without additional exposure to automated travel)?*

As with the comparisons made to determine whether driving performance was affected by repeated travel in the automated lane, the a priori comparisons that were to be made to determine the answer to this question were conditional. In this case, they depended both on whether there had been an AHS effect and on whether there were diurnal effects on the commuter's driving performance.

If a driving measure was unaffected by travel in the AHS, then an AHS effect could not persist from one session to the next. On the other hand, for those measures where an AHS effect was found, it was necessary to determine whether there were also diurnal effects.

If no diurnal effects had been found, the possibility of AHS effects persisting from one session to the next would have been investigated directly. A series of comparisons would have been made between the post-AHS driving performance data obtained in the morning and the pre-AHS performance obtained in the afternoon, and between the post-AHS driving performance data obtained in the afternoon and the pre-AHS performance obtained the next morning. However, as will be reported later, the time of day did affect the driving performance measures.

Because there were also diurnal effects with the driving performance measures that were affected by travel in the AHS, the more complex series of comparisons planned for this situation were carried out. For each of the three driving performance measures that was affected by the AHS, the difference between its pre-AHS value and its value in each of the seven post-AHS 1-min segments was computed for every session. Then, the differences between the pre-AHS and post-AHS values were compared from session to session, using the Tukey Studentized range test, with the Tukey-Kramer modification.[22-24] If these differences decreased from session to session, and if the pre-AHS driving performance obtained on the first morning of the experiment was significantly different from the post-AHS performance on the last morning, it could be concluded that there was an AHS effect that had persisted from one session to the next.

Steering Instability

Steering instability is the first of the three driving measures for which differences were found when the driver's initial driving performance data were compared with his/her performance after traveling in the automated lane. To determine whether this steering instability difference persisted and carried over from one experimental session to the next, the differences between the pre-AHS and post-AHS values were compared from session to session. The Tukey Studentized range test, with the Tukey-Kramer modification, was used to make the comparisons. The tests showed that the differences between the steering instability in the pre-AHS section and the steering instability in six of the seven post-AHS 1-min time segments, which were obtained in the first experimental session on Wednesday, were significantly larger than the differences between the pre-AHS section and the same 1-min periods in many of the sessions, particularly those on Thursday, Friday, and Monday afternoons. These differences can be seen in figure 12.

As was mentioned earlier, and as can be seen in figure 12, after traveling under automated control for the first time on Wednesday morning, the commuter's steering instability decreased by 40 percent. This decrease was maintained through the end of the post-AHS section of that session.

When the commuter drove in the morning the next day (Thursday), the steering instability in the pre-AHS section was midway between the pre-AHS steering instability levels for the first two sessions on the first day. In addition, in the post-AHS section of the Thursday morning session, the instability level dropped to the same post-AHS steering instability level that was obtained on the first day. Then on Thursday afternoon, in the pre-AHS section at the start of the fourth session, the instability level was as low as it was in the pre-AHS section at the start of the second session on the first day.

Figure 12 shows that the pattern of steering instability scores that was obtained during the morning and afternoon sessions on Thursday—described above—was very similar to the patterns obtained on Friday and Monday. On both the latter days, at the start of the morning session, the pre-AHS steering instability level was midway between the pre-AHS levels of the first two sessions on the first day of the experiment; it then dropped again and stayed at the lower level for the pre-AHS section at the beginning of the afternoon session. [No statistical tests were run to confirm these patterns. No parametric statistical tests to examine whether distributions are significantly alike are available.]

The lowered steering instability levels that were obtained in the pre-AHS section of the afternoon sessions on all 4 days indicate that this effect of traveling under automated control did, in fact, persist from the morning to the afternoon. Similarly, the steering instability levels found in the pre-AHS section of the morning sessions on the last 3 days of the experiment indicate—when they are compared to the pre-AHS steering instability level obtained on the first day of the experiment—that this effect of traveling under automated control also persisted overnight from the afternoon session to the morning session on the next day. However, it should be noted that the extent to which this effect persisted overnight was not as pronounced as the extent to which it persisted from morning to afternoon.

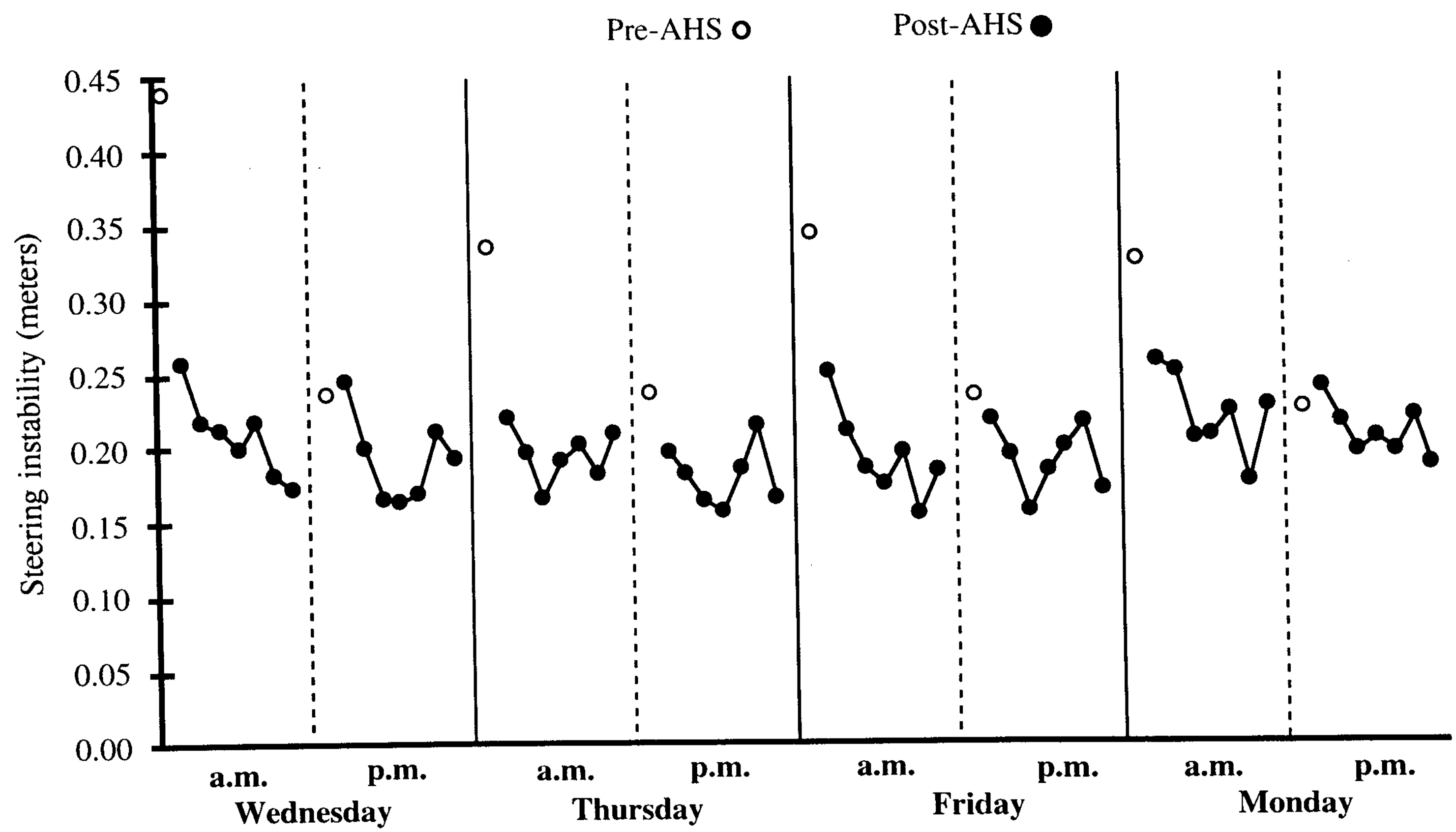


Figure 12. Steering instability for the pre-AHS section and the first, second, third, fourth, fifth, sixth, and seventh 1-min segments of the post-AHS section of all eight sessions.

There are two other observations that are worthy of note in figure 12. First, in addition to demonstrating the effect of traveling under automated control, the figure also shows the nature of the diurnal effect on steering instability. This diurnal effect occurs primarily in the pre-AHS section of the sessions—the steering instability level was consistently higher in the pre-AHS section of the morning sessions than it was in the pre-AHS section of the afternoon sessions. Second, the reduction in the steering instability that occurred in each session after the driver had traveled in the automated lane did not change from one session to the next. There were essentially no further reductions in any of the remaining seven sessions that were below the level to which the steering instability dropped in the post-AHS section of the first session of the experiment.

Velocity Instability

Velocity instability was the second driving measure for which differences were found when the driver's initial driving performance data were compared with his/her performance after traveling in the automated lane. As with steering instability, in order to determine whether the velocity instability difference persisted from one experimental session to the next, the differences between the pre-AHS and post-AHS values were compared from session to session. As before, the Tukey Studentized range test, with the Tukey-Kramer modification, was used to make the comparison. The test indicated that there was one statistically significant difference: The difference between the velocity instability during the pre-AHS section of the first session and the seventh 1-min segment of the post-AHS section of the first session was significantly greater than the difference between the velocity instability during the pre-AHS section of the second session and the seventh 1-min segment of the post-AHS section of the second session. This difference can be seen in figure 13, which plots the mean velocity instability of the commuters in the pre-AHS section and in each of the seven 1-min segments of the post-AHS section of all eight sessions.

As with the pattern of steering instability scores (shown in figure 12), the pattern of velocity instability scores throughout the eight sessions that is shown in figure 13 suggests that the AHS effect did persist from the end of one session to the beginning of the next. A similar pattern of scores was obtained during the morning and afternoon sessions on Thursday, Friday, and Monday. On each of the 3 days, at the start of the morning session, the pre-AHS velocity instability was approximately 80 percent of that in the Wednesday morning pre-AHS section, before the commuter had experienced automated travel. At the start of the afternoon session, the pre-AHS velocity instability level was approximately 60 percent of the Wednesday morning pre-AHS level. [As with the steering instability data, no statistical tests were run to confirm the pattern of

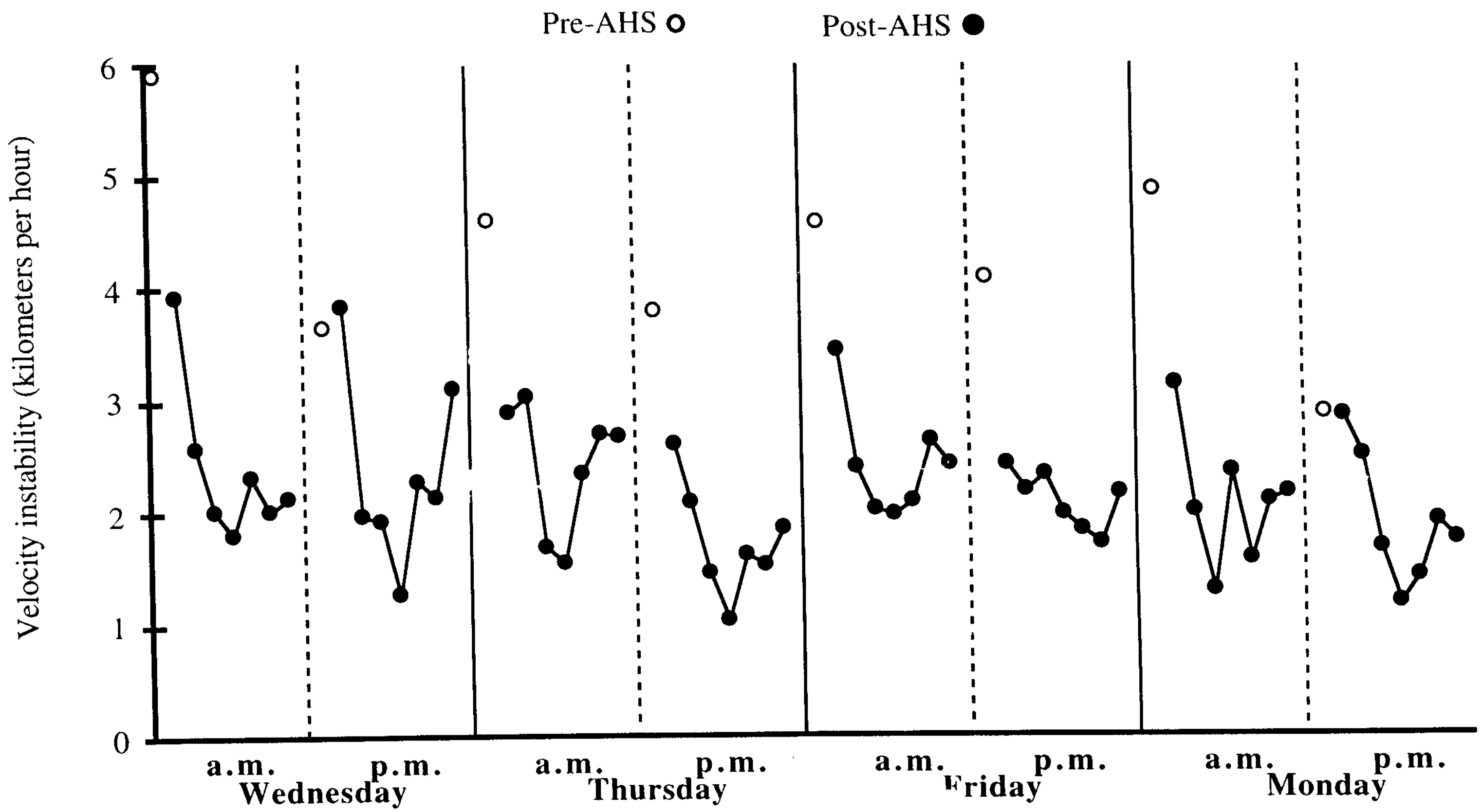


Figure 13. Velocity instability for the pre-AHS section and the first, second, third, fourth, fifth, sixth, and seventh 1-min segments of the post-AHS section of all eight sessions.

velocity instability scores—in part because no parametric statistical tests to examine whether distributions are significantly alike have been developed.]

Like figure 12, figure 13 shows the nature of the diurnal effect on velocity instability of traveling under automated control. Once again, the diurnal effect occurs primarily in the pre-AHS section of the sessions—the steering instability level was higher in the pre-AHS section of the morning sessions than it was in the pre-AHS section of the afternoon sessions.

Velocity Fluctuations

The third driving measure for which differences were found when the driver's initial driving performance data were compared with his/her post-AHS performance after traveling in the automated lane was the number of velocity fluctuations. As with the other two measures, in order to determine whether the difference in the number of velocity fluctuations persisted from one experimental session to the next, the differences between the pre-AHS and post-AHS numbers were compared from session to session. Once again, the Tukey Studentized range test, with the Tukey-Kramer modification, was used to make the comparison. Statistically significant differences were found for only the seventh 1-min segment of the post-AHS time period. The difference between the number of velocity fluctuations during the pre-AHS section of the seventh session and the seventh 1-min segment of the post-AHS section of the seventh session was significantly greater than the differences between the velocity fluctuations during the pre-AHS section of the second, third, and eighth sessions, and the seventh 1-min segment of the post-AHS section of the second, third, and eighth sessions, respectively. These differences are shown in figure 14, which presents a plot of the mean number of velocity fluctuations in the pre-AHS section and each of the seven 1-min segments of the post-AHS section of all eight sessions.

In contrast to figures 12 and 13, which suggest that the AHS effects on steering instability and velocity instability persist from one session to the next, the picture provided by figure 14 is less clear—there is less similarity in the patterns of scores on the second, third, and fourth days than there was for the two sets of instability scores. However, there are some indications that the AHS effect may persist from one session to the next—in particular, there were increases in the number of velocity fluctuations in the pre-AHS section of the Wednesday afternoon, Thursday morning, and Thursday afternoon sessions as compared to the number of fluctuations in the pre-AHS section of the Wednesday morning session; and there were increases in the number of fluctuations in the pre-AHS section on Monday afternoon as compared to the Monday morning session.

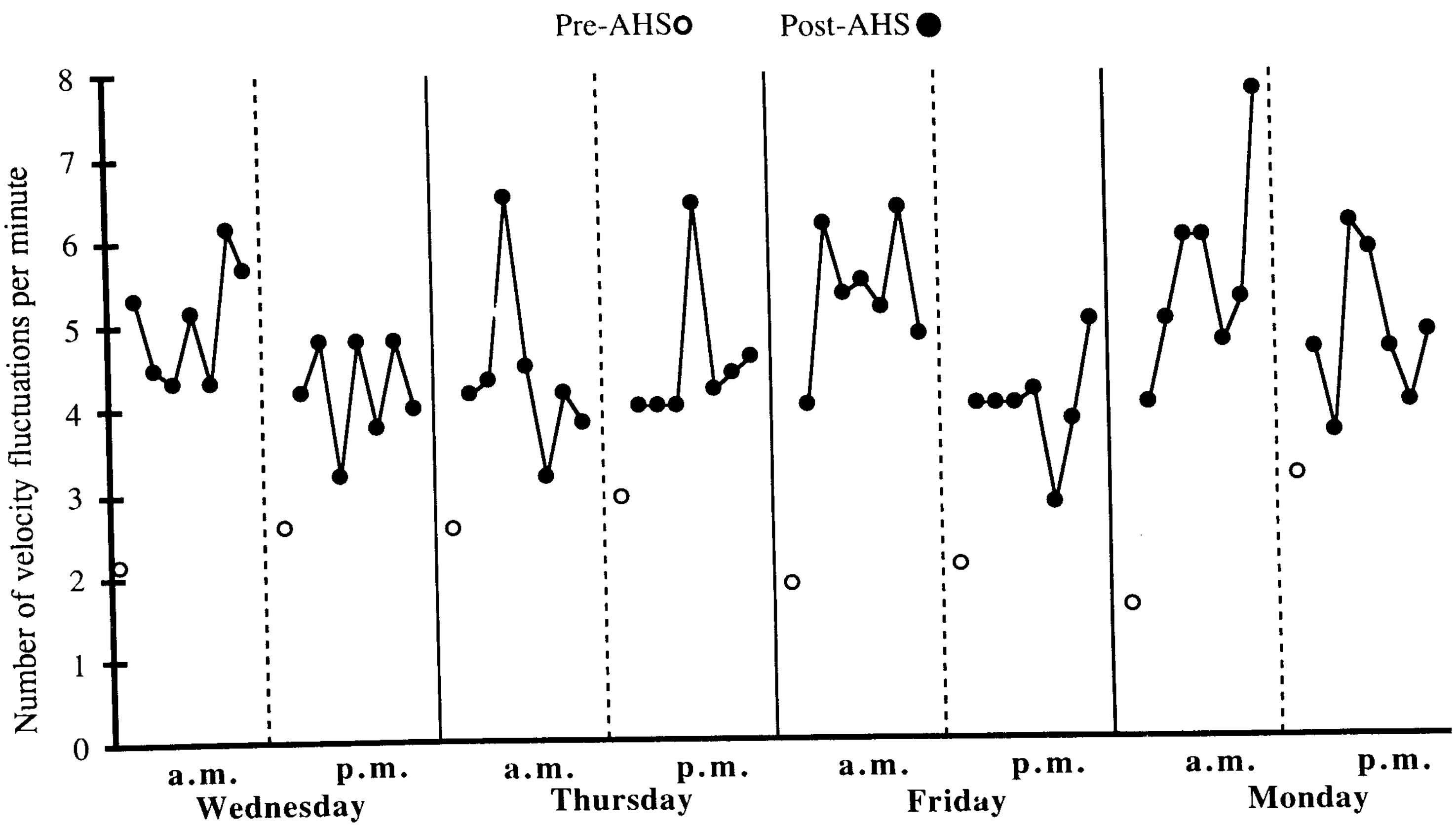


Figure 14. Number of velocity fluctuations per minute for the pre-AHS section and the first, second, third, fourth, fifth, sixth, and seventh 1-min segments of the post-AHS section of all eight sessions.

DIURNAL EFFECTS

Manual dexterity and horizontal scanning are among the areas of performance where diurnal effects are found.(16) Since these are behaviors that may be utilized in driving, it was possible that there might be diurnal effects on driving performance that could be confounded with the effects of exposure to the AHS on commuters. A series of analyses was performed in order to discern whether or not there was a difference in the morning and afternoon driving performances of the six subjects so that possible confounding effects could be eliminated. If no diurnal effects were found, then the comparison exploring the effects of traveling in the AHS could have been made between the morning session on the first day of the experiment and the final afternoon session. On the other hand, if diurnal effects were found, this comparison could only have been made between the morning sessions on the first and last days.

To determine whether the commuter's driving performance was affected by the time of day, data obtained in the morning and afternoon sessions on Friday and Monday were compared. Data from Wednesday and Thursday—the first two days on which the experiment was conducted—were not used in these comparisons. For those driving measures that were affected by travel in the automated lane, it was thought that the initial effect of experiencing the AHS might, because of its novelty, have been large enough to overwhelm what was a real, but relatively small, diurnal effect. Comparisons were made between the driving performance measures obtained in the morning and afternoon sessions on both Friday and Monday. The Dunn-Bonferroni procedure was used to make these pairwise comparisons of the data collected in the pre-AHS sections of the journey and in the seven 1-min post-AHS time periods.(25)

Several of the differences between the data obtained in the morning and afternoon were found to be statistically significant ($p < 0.05$). Some of these differences had an impact on the analysis of the effects of traveling in the AHS. Specifically, on Friday, there was a significant difference in the number of steering oscillations that occurred in the morning and afternoon sessions during the fourth post-AHS time period—the mean number of oscillations was 12.6 per minute in the morning and 11.1 per minute in the afternoon. There was also a significant difference in the velocity instability obtained in the morning and afternoon for the seventh post-AHS time period—the mean instability was 2.4 km/h (1.5 mi/h) for the morning drive and 1.5 km/h (0.9 mi/h) for the afternoon drive. The third significant difference for the Friday data was for the velocity drift obtained in the morning and afternoon sessions for the first post-AHS time period—the means were -0.00015 m/m (-0.00015 ft/ft) for the morning and 0.00084 m/m (0.00084 ft/ft) in the afternoon. Also on Friday, differences were found, using the chi-square test, for one of the driving measures that could not be segmented. When the number of lane changes was totaled over the complete post-AHS drive, significantly fewer lane changes ($\chi^2(1) = 4$, $p < 0.05$) were found in the post-AHS morning section of the journey than were found in the afternoon; there were 12 and 24 lane changes, respectively.

There were three significant differences in the driving performance data obtained on Monday as well. The steering instability that occurred in the pre-AHS section in the morning was greater than the instability that was found in the afternoon; the mean steering instabilities were 0.33 m (1.1 ft) and 0.23 m (0.8 ft), respectively. There were significantly fewer velocity fluctuations in the pre-AHS section in the morning than there were in the afternoon—there were 1.59 and 3.16 fluctuations per minute, respectively. Finally, one post-AHS diurnal difference was found on Monday. There was a statistically significant difference in average velocity obtained in the morning and the afternoon sessions in the fourth post-AHS time period; the means were 88.2 km/h (54.8 mi/h) and 84.0 km/h (52.1 mi/h), respectively.

As already mentioned, because driving behavior was affected by the time of day, changes were made in the way that the effects of the AHS were analyzed.

DAY-TO-DAY EFFECTS

Possible day-to-day effects were analyzed using the Tukey Studentized range test, with the Tukey-Kramer modification.(22-24) Comparisons were made of the driving performance data that were obtained in the pre-AHS section of the drive and for each of the seven post-AHS time periods across all four morning and afternoon sessions.

Only two significant effects were found when the morning data were analyzed. There was a difference in the number of steering oscillations that occurred in the sixth post-AHS time period—specifically, there were more oscillations on Thursday (14.2 oscillations per minute) than there were on each of the other days [Wednesday (11.0 oscillations), Friday (10.6 oscillations), and Monday (10.3 oscillations)]. There were also significantly more oscillations in the seventh post-AHS time period on Wednesday (14.6 oscillations per minute) than there were on Monday (8.7 oscillations per minute).

One of the five significant differences that were found in the afternoon also involved steering oscillations—there were more steering oscillations during the seventh post-AHS time period on Wednesday (14.3 per minute) than there were on either Thursday (8.2 per minute) or Monday

(9.2 per minute). The average velocity also differed significantly during the seventh post-AHS time period for Wednesday and Thursday; the velocities were 87.9 km/h (54.6 mi/h) and 82.7 km/h (51.4 mi/h), respectively.

The remaining three differences that were found in the afternoon all involved velocity instability. Velocity instability was larger in the first post-AHS time period on Wednesday than it was on Friday—the means were 3.8 km/h (2.4 mi/h) and 2.4 km/h (1.5 mi/h), respectively. The velocity instability also differed significantly during the seventh post-AHS time period; it was higher, at 3.1 km/h (1.9 mi/h), on Wednesday than on Friday or Monday, when it was 1.5 km/h (0.9 mi/h) and 1.7 km/h (1.0 mi/h), respectively. Finally, for the fourth post-AHS time period, the velocity instability was significantly higher, at 2.0 km/h (1.2 mi/h), on Friday than it was on either Thursday, when it was 1.0 km/h (0.62 mi/h), or Monday, when it was 1.2 km/h (0.7 mi/h).

Differences were also found for the number of lane changes—one of the driving measures that was not segmented. When the number of lane changes was totaled over the complete post-AHS drive in the afternoon, and the chi-square test was used, a statistically significant effect was found ($\chi^2(3) = 17.1, p < 0.05$). The lane changes made in the post-AHS sections of the afternoon sessions on Wednesday, Thursday, Friday, and Monday numbered 9, 4, 24, and 15, respectively. Because of the nature of the chi-square test, all that can be added about these data is that it is clear that the number of lane changes made in the post-AHS section of the Thursday afternoon session was significantly smaller than the number made in the post-AHS section of the Friday afternoon session.

MINIMUM FOLLOWING DISTANCE

The minimum following distance[2] was determined for the whole of the post-AHS section in each session, rather than for each of the seven 1-min segments into which that section was divided for

[2] In order to determine the minimum following distance for each driver, the following procedure was used. First, throughout the two data collection time periods, the gap between the front bumper of the driver's car and the back bumper of the vehicle ahead was recorded 30 times per second. Second, if the driver changed lanes, the data obtained during the lane change were eliminated from consideration. Third, whenever the gap between the driver's vehicle and the vehicle ahead exceeded 440 m (1443 ft), the data were eliminated from consideration. Fourth, if after a break in the data the gap increased continuously, the lowest point was ignored (if the gap was continuously increasing, this may have been because the driver was uncomfortable with the gap and had reduced speed to increase it). Fifth, if before a break in the data the gap decreased continuously, the lowest point was also ignored (if the gap was continuously decreasing, this may have been because the gap was still larger than the minimum following distance that was acceptable to the driver). Sixth, the lowest point was selected. Seventh, it was determined whether there were gap data for at least 10 s around the lowest point—if there were less than 10 s of data, they were discarded. Eighth, the gap data acquired in any period that was 10 s or more were examined—if during this 10-s period the gap exceeded the lowest point by 133 percent, the data were discarded (this is because the lowest point may have occurred because another vehicle moved into the lane ahead of the driver, leaving a gap that was smaller than was

the analysis of the lane-keeping and speed-control measures. Then, using an ANOVA, the minimum following distances for the pre-AHS section of the first session on Wednesday morning were compared with the minimum following distances obtained in the post-AHS section of the first session on Wednesday morning, Friday morning, and Monday morning. No significant differences were found for any of these comparisons.

This result differs from that obtained by Bloomfield, Levitan, Grant, Brown, and Hankey.(8) They found that the mean minimum following distance decreased after the driver had traveled under automated control—from 25.5 m (83.7 ft) to 19.7 m (64.4 ft). Since the vehicles were traveling at approximately 88.6 km/h (55 mi/h), the distance decreased from 1.01 s to 0.8 s. A total of 36 drivers traveled under automated control in the Bloomfield et al. experiment—only 6 drivers participated in the present experiment, and the variability among them, combined with the relatively small sample size, may have prevented a similar effect from emerging from the analysis. To examine this possibility further, the sign test was used to conduct a pairwise comparison between the minimum following distances in the pre-AHS section and in the post-AHS section of all eight sessions for all six drivers. The test showed that the minimum following distance for the post-AHS section was shorter than the pre-AHS minimum following distance more often than it was longer ($p = 0.0239$)—indicating that after traveling under automated control, there may have been a tendency for the commuters to drive closer to the vehicle ahead than they had in the pre-AHS section of the sessions.

There were insufficient data to determine whether there were diurnal or day-to-day effects on the minimum following distance.

LANE-CHANGE GAP ACCEPTANCE

There were enough lane-change data to make it possible to determine the smallest gaps that the commuters were willing to accept when they changed lanes. As they were driving along the expressway during the 16 data collection periods (pre-AHS and post-AHS data were obtained in the morning and afternoon sessions for 4 days), the commuters changed lanes periodically. Every time a lane change was completed, the distance between the back bumper of the vehicle ahead and the front bumper of the vehicle behind in the adjacent lane was recorded. During the 16 data collection periods, 197 lane changes were recorded. The distribution of the lane changes is shown in table 4. There were no significant differences among the number of lane changes based

acceptable to the driver who, as a result, reduced speed to increase the gap). Ninth, if the data met all the criteria listed above, the lowest point was reported as the minimum following distance for the driver.

Table 4. Number of lane changes per segment.

		Pre-AHS	Post-AHS
Wednesday	a.m.	16	8
	p.m.	9	9
Thursday	a.m.	18	12
	p.m.	12	4
Friday	a.m.	12	12
	p.m.	13	24
Monday	a.m.	12	11
	p.m.	10	15

upon any of the a priori comparisons related to exposure to the AHS. However, significant diurnal and day-to-day effects were found (they have been described above).

The gaps that occurred in the pre-AHS and post-AHS sections of the drives were arranged in ascending order. Then, all gaps that were less than 350 m (1148 ft) were plotted in figures 15 and 16—350 m (1148 ft) was an arbitrary cut-off, equivalent to a 14-s gap for vehicles traveling at the 88.6-km/h (55-mi/h) speed limit.

Figures 15 and 16 show that a number of smaller gaps are clustered between 40 m (131 ft) and 60 m (197 ft). After this cluster, the shape of the functions appears to change—in figure 16, there is a break in the data at this point, after which most of the remaining gaps are greater than 100 m (328 ft). In this experiment, the commuters drove at speeds close to 88.6 km/h (55 mi/h) in both the pre-AHS and post-AHS data collection periods. For a driver traveling at 88.6 km/h (55 mi/h), a gap of 100 m (328 ft) is a 4.1-s gap. It is likely that the gaps of 100 m (328 ft) were much bigger than the minimum gap that would have been acceptable to the driver—and it is clear that many lane changes occurred when the gap was much larger than the minimum acceptable gap. However, the gaps clustered between 40 m (131 ft) and 60 m (197 ft)—which are gaps of 1.6 s and 2.4 s, respectively, for a driver traveling at 88.6 km/h (55 mi/h)—may have been close to the minimum acceptable gap. Bloomfield, Levitan, Grant, Brown, and Hankey obtained similar results when considering the gaps accepted by drivers making lane changes.(8) As can be seen from figures 15 and 16, there are almost no lane changes with gaps smaller than 40 m

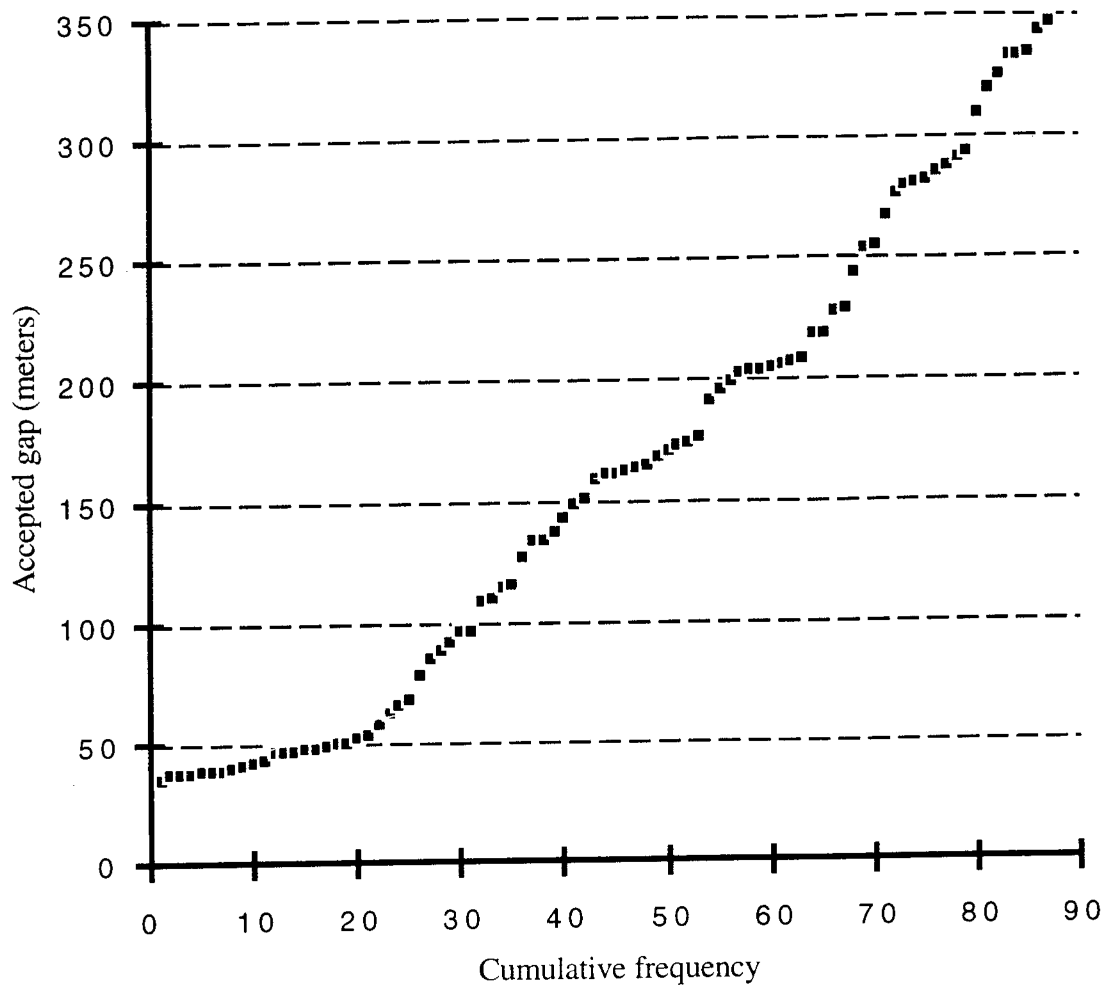


Figure 15. Scatterplot showing gaps shorter than 350 m (1148 ft) that were accepted when lane changes were made while the commuter was driving in the pre-AHS section of the sessions.

(131 ft). There is no indication that there is a difference in minimum gap acceptance before and after the commuter traveled under automated control.

INCURSIONS

Lane incursions can also provide useful information about the minimum acceptable gap for changing lanes. During the data collection periods in this experiment, there were a number of lane incursions, i.e., occasions when the driver began to change lanes, but, for some reason, did not complete the maneuver, and instead returned to the lane from which he/she started. When an

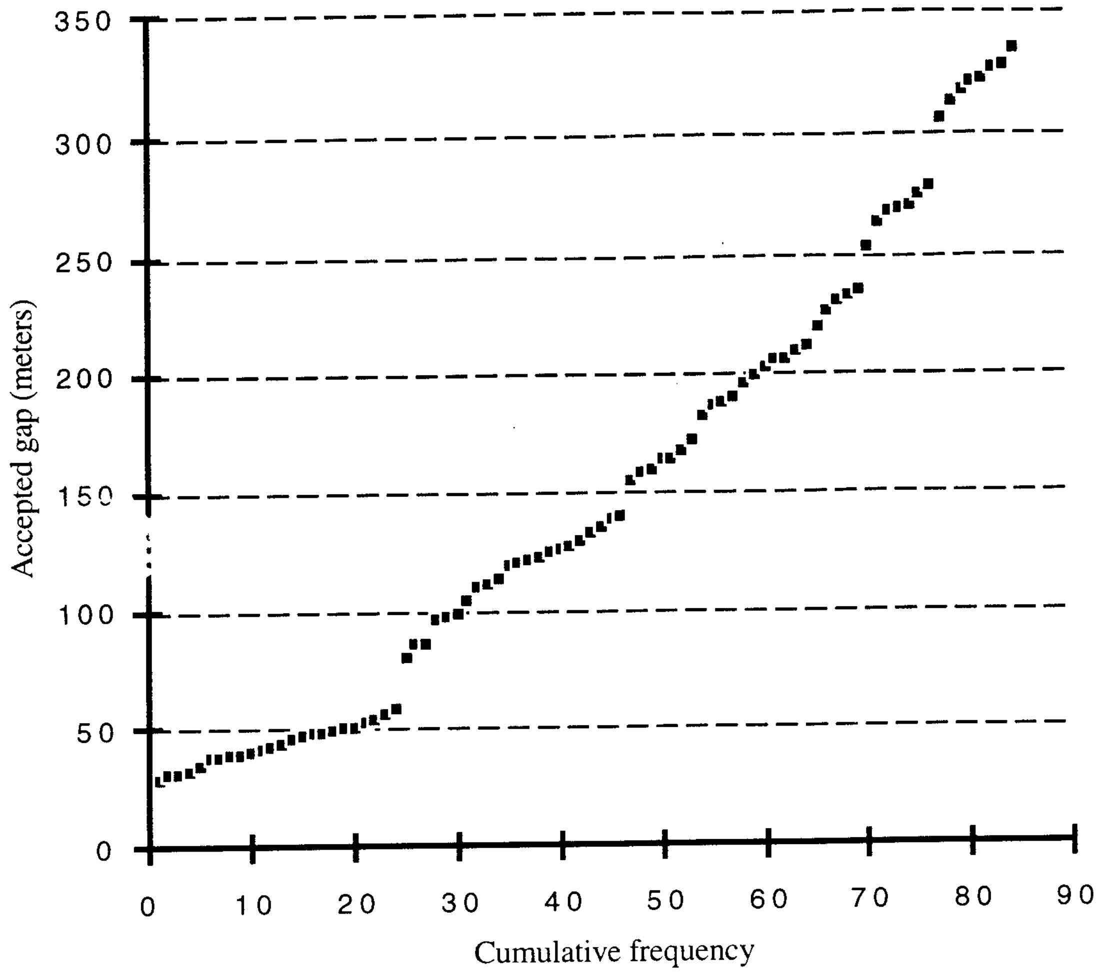


Figure 16. Scatterplot showing gaps shorter than 350 m (1148 ft) that were accepted when lane changes were made while the commuter was driving in the post-AHS section of the sessions.

incursion occurred, the distance between the back bumper of the vehicle ahead and the front bumper of the vehicle behind in the adjacent lane was recorded. There were 79 incursions during the 16 data collection periods (pre-AHS and post-AHS data were obtained in the morning and afternoon sessions for 4 days). The distribution of the incursions is reported in table 5. Due to the relatively low numbers of incursions in many of the cells, no statistics were run on the data.

The incursion gaps that occurred in the pre-AHS and post-AHS sections of the drives were arranged in ascending order. Then, all those gaps that were less than 350 m (1148 ft) were plotted in figures 17 and 18. Inspection of figures 17 and 18 reveals that the incursion-gap function is

Table 5. Number of incursions per segment.

		Pre-AHS	Post-AHS
Wednesday	a.m.	9	11
	p.m.	2	3
Thursday	a.m.	8	3
	p.m.	7	3
Friday	a.m.	9	6
	p.m.	4	2
Monday	a.m.	4	3
	p.m.	1	4

similar to that seen for the lane-change gaps in figures 15 and 16. There is a cluster of incursion gaps between 50 m (164 ft) and 60 m (197 ft), then there is a break in the function similar to that seen in figure 16, with most of the remaining gaps being longer than 100 m (328 ft).

The 50-m (164-ft) to 60-m (197-ft) region within which the incursion gaps cluster is similar to the region shown in figures 15 and 16 within which the smallest lane-change gaps cluster. Since the incursion gaps in this region were large enough for the driver to begin a lane-change maneuver, but then, on consideration, even as the maneuver was in progress, were judged to be too small, they are probably close in size to the minimum acceptable gap. However, when there were lane incursions with rejected gaps longer than 100 m (328 ft), it is likely that the driver abandoned the lane change for some other reason—one not connected with the size of the gap. Bloomfield, Levitan, Grant, Brown, and Hankey obtained similar results when considering the gaps rejected by drivers when lane incursions occurred.[8]

There were no rejected gaps shorter than 50 m (164 ft) in the pre-AHS section of the sessions (as can be seen in figure 17). There were, however, five incursions that were shorter than this in the post-AHS section of the sessions (see figure 18)—this provides no more than a hint that there may be an AHS effect, given that only five of these relatively small incursions occurred in 336 min (there were eight 7-min post-AHS sessions for each of the six drivers).

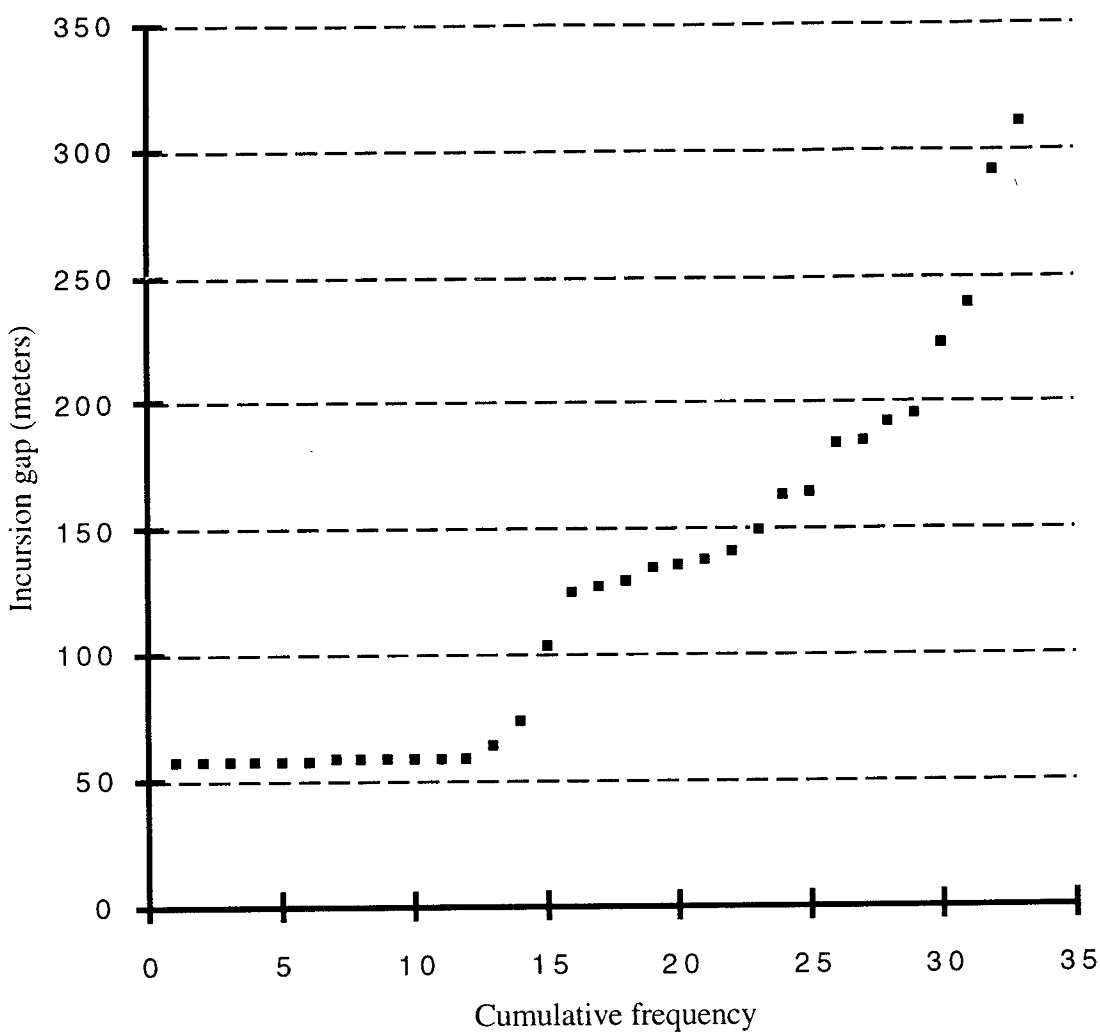


Figure 17. Scatterplot showing gaps shorter than 350 m (1148 ft) that were rejected when lane incursions occurred while the commuter was driving in the pre-AHS section of the sessions.

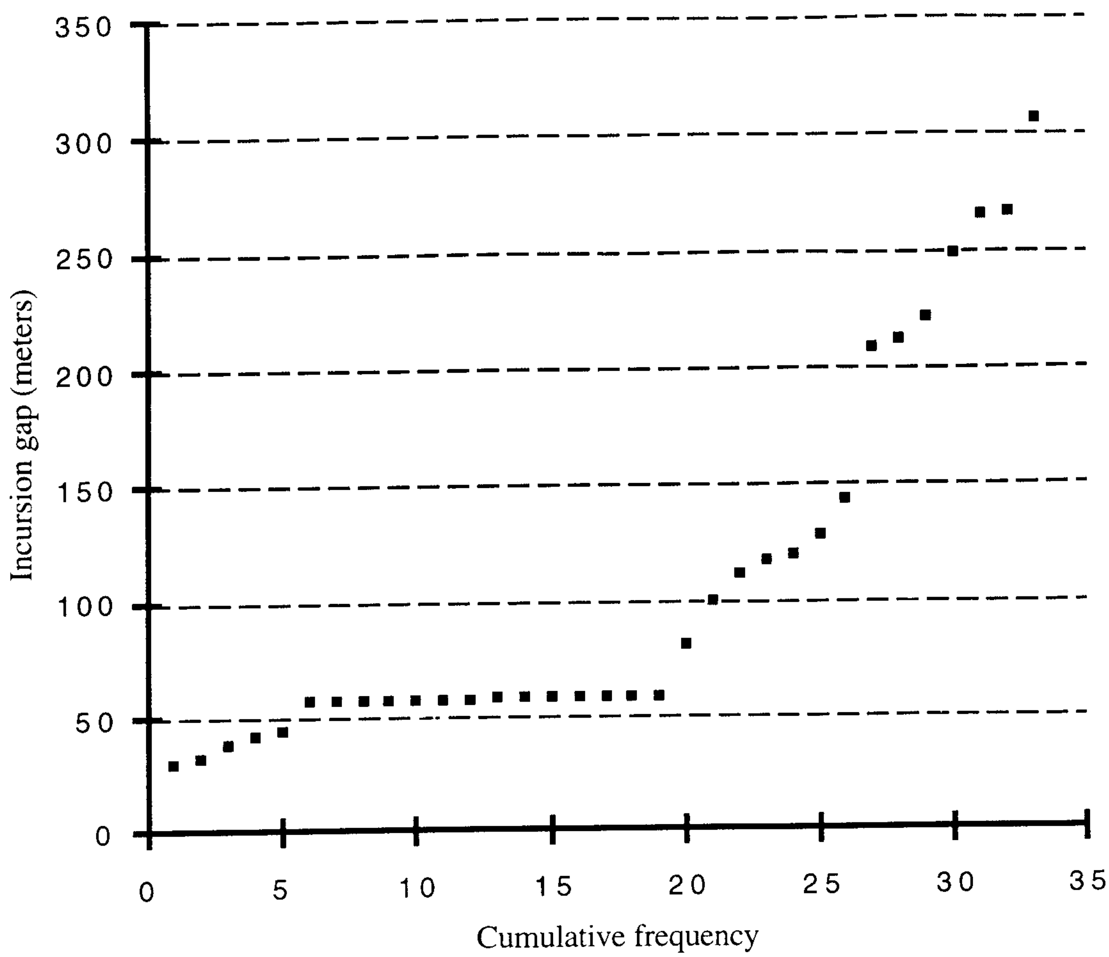


Figure 18. Scatterplot showing gaps shorter than 350 m (1148 ft) that were rejected when lane incursions occurred while the commuter was driving in the post-AHS section of the sessions.

ACCEPTED VERSUS REJECTED GAPS

Since the functions obtained for lane-change gaps and incursion gaps are very similar, it is reasonable to ask if, and how, they might be related, e.g., do the drivers who have the shortest lane-change gaps also have the shortest incursion gaps? Alternatively, do the drivers who have the shortest lane-change gaps also have very few incursions?

In order to explore the relationship between lane-change and incursion gaps, the smallest gap that each driver drove into when making a lane change was compared with the smallest incursion gap that he/she rejected. Pairs of values were found for each commuter in each of the eight sessions—for the purposes of this comparison, the pre-AHS and post-AHS data were combined within each session. If the commuter did not have both an incursion and a lane change during a session, no data were used for that commuter for that session. Figure 19 shows a plot of the minimum lane-change gaps accepted by each commuter in each session plotted in ascending order—the figure also shows the minimum rejected incursion that is associated with each minimum lane-change gap for each commuter in each session. Figure 20 reverses figure 19 by presenting a plot of the minimum rejected incursion gaps plotted in ascending order, with the minimum accepted lane-change gap for that commuter also shown.

As can be seen from figures 19 and 20, there does not appear to be a straightforward correlation between the gaps that the commuters accepted and the gaps that they rejected—suggesting that the drivers who have the smallest lane-change gaps do not have the smallest incursion gaps.

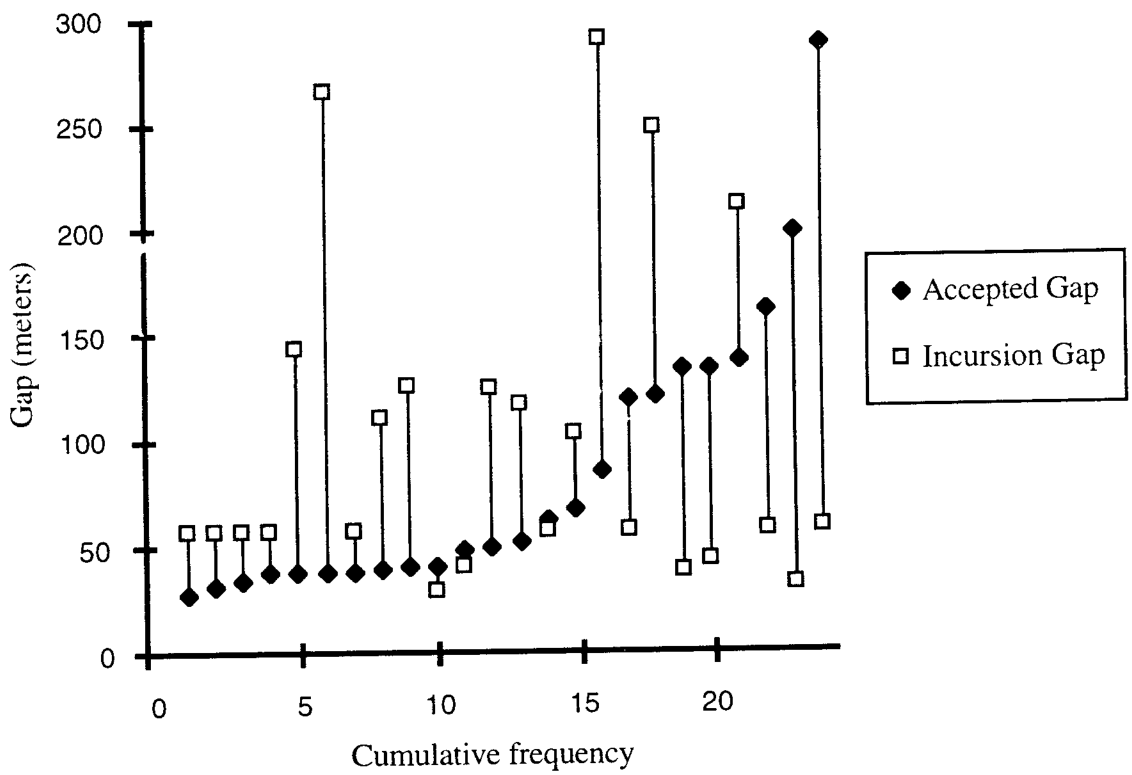


Figure 19. Scatterplot showing the minimum accepted lane-change gaps and the associated minimum rejected incursion gaps.

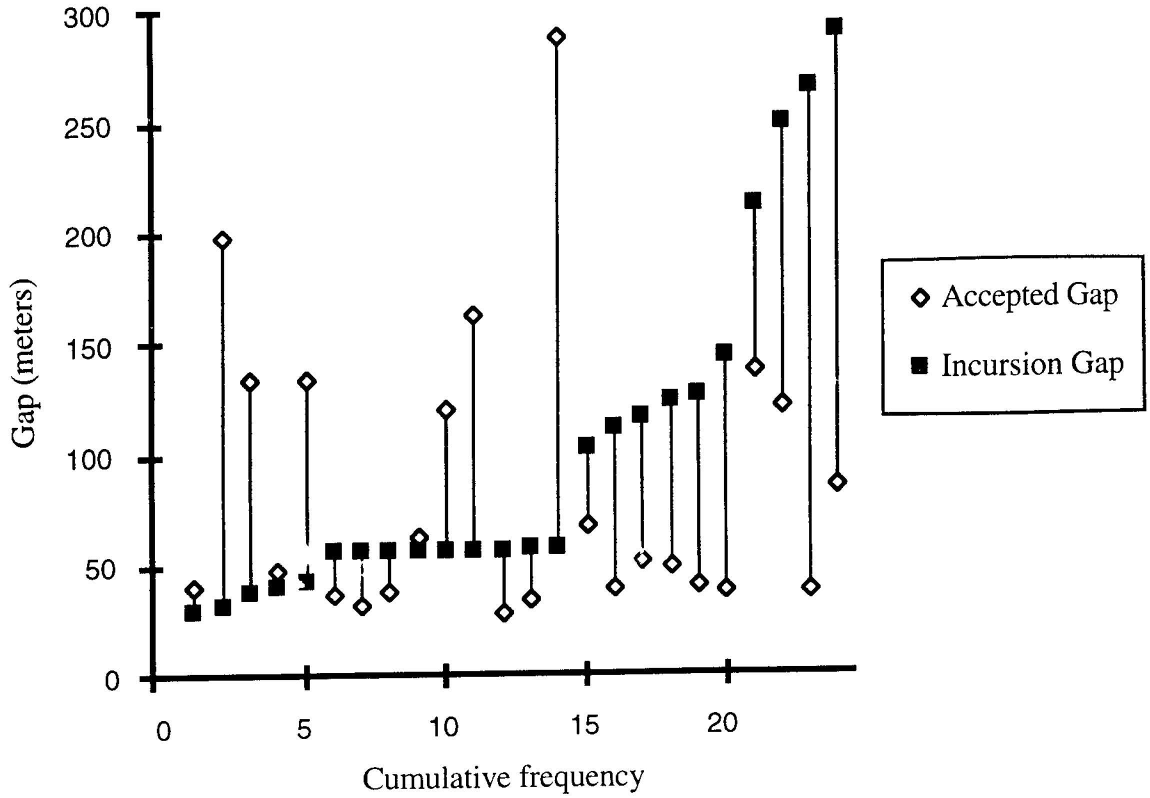


Figure 20. Scatterplot showing the minimum rejected incursion gaps and the associated minimum accepted lane-change gaps.

The alternative suggestion made at the beginning of this section—that the drivers who have the smallest lane-change gaps may have very few incursions—was also examined. The correlation between these two variables was not statistically significant.[3]

It should be noted that when the minimum gaps for each commuter in each session are obtained, they are clustered in the region between 40 m (131 ft) and 60 m (197 ft) for both accepted and rejected gaps. Drivers are equally as likely to reject a gap in this region as they are to accept it. This indicates that the minimum gap acceptable for a lane change is in this region. At the 88.6-km/h (55-mi/h) speed at which the commuters traveled, the midpoint of this range (50 m) is equivalent to a 2.0-s gap.

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3 There were relatively few incursions for each driver. It should be pointed out that because of their scarcity, this experiment probably did not provide an adequate test of the hypothesized relationship—the driving periods would have had to have been considerably longer for the test to be adequate.

DRIVER ACCEPTANCE OF THE AHS

In addition to exploring how the commuter's driving performance changed as a result of traveling under automated control, it was also possible to obtain information related to how the commuter's trust in the AHS changed over the course of the experiment. The length of time that the commuter waited before removing both hands from the steering wheel after pressing the button to engage the automated system was determined by video analysis. The average time that the commuter waited after engaging the AHS before removing both hands from the wheel is depicted in figure 21. It is evident from this figure that the more often commuters used the automated system, the less time they waited before removing their hands from the wheel, and the more it might be inferred that the commuter came to trust the AHS to take control of the vehicle.

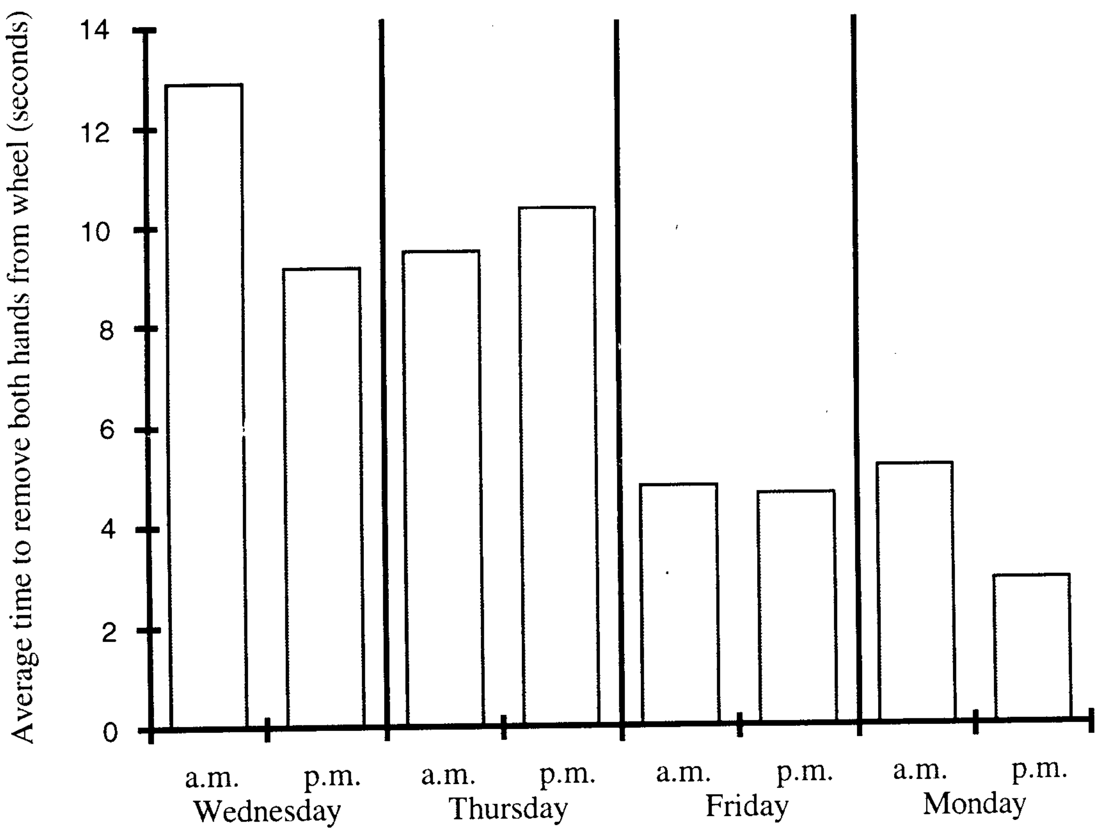

Figure 21. Average time after the AHS was engaged that the commuter waited before removing both hands from the steering wheel.

THE QUESTIONNAIRE

The questionnaire developed for this experiment was presented to the commuter on two occasions—the first was immediately after the initial session on Wednesday morning, the second was after the final session on Monday afternoon. The questionnaire was identical on both occasions. A copy of the questionnaire is presented in appendix 3. A scale ranging from 0 to 100, with negatively and positively worded anchors at the ends, was provided for each question. The commuters were asked to rate their responses as whole numbers between 0 and 100. A space was provided next to the question and scale. Two dichotomous questions (numbers 11 and 25) asked the drivers to check a box indicating either yes or no. These items were scored as zero for no and one for yes.

Simulator Realism

The first six questions of the questionnaire were presented in order to gather the commuter's opinion on the realism of the Iowa Driving Simulator. The average responses ranged from 68.3 to 95.0, indicating that drivers had positive attitudes toward the simulator. The responses obtained after the first and last sessions were compared using the t-test—the test failed to show any statistically significant differences for these six questions. The average response made to each question after the first and last sessions is reported in table 6 below. The responses indicate that drivers enjoyed driving in the simulator a lot (question 1), felt that the simulator was similar to driving their own car (question 2), and found the view out of the windshield to be realistic (question 3). Also, the drivers considered the sounds in the simulator to be moderately realistic (question 4), felt that the vehicle motion was realistic (question 5), and felt very well while driving the simulator (question 6).

Designated AHS Velocity and Intra-String Gap

Questions 7 and 8 (table 7) dealt with the designated AHS velocity and the intra-string gap, i.e., the gap between the commuter's vehicle and the vehicle ahead when they were both part of a string of automated vehicles. The t-test comparisons conducted to determine if the mean responses from the first session and last session were statistically different yielded no significant results. The responses for question 7 indicate that the commuters would have preferred a faster speed. The responses for question 8 show that the commuters would have preferred a longer intra-string gap when under automated control.

Table 6. Simulator realism.

Question	First Session Mean	Last Session Mean
1. How much did you enjoy driving the simulator? 0. Not at all 100. A lot	89.2	95.0
2. How did driving in the simulator compare to driving in your car? 0. Very different 100. Very similar	75.8	76.7
3. How realistic was the view out of the windshield in the simulator? 0. Very artificial 100. Very realistic	78.3	83.0
4. How realistic were the sounds in the simulator? 0. Very artificial 100. Very realistic	68.3	74.2
5. How realistic was the vehicle motion in the simulator? 0. Very artificial 100. Very realistic	71.7	74.2
6. While driving the simulator, how did you feel? 0. Did not feel well 100. Felt fine	94.2	95.0

Table 7. Designated AHS velocity and intra-string gap.

Question	First Session Mean	Last Session Mean
7. In this study, when your car was under automatic control, how did you feel about the speed at which you traveled? 0. Would have preferred to go much slower 100. Would have preferred to go much faster	80.8	66.7
8. In this study, when your car was under automatic control, how did you feel about the separation distance between you and the car ahead? 0. Would have preferred a much longer separation 100. Would have preferred a much shorter separation	30.0	44.2

AHS Messages

Question 9 dealt with the clarity of the AHS messages that were presented during this experiment. As table 8 shows, the average response after both sessions was 100, indicating that the AHS messages were very easy to understand.

Table 8. AHS messages.

Question	First Session Mean	Last Session Mean
9. How understandable was the message saying that you should take control of your car? 0. Very hard to understand 100. Very easy to understand	100.0	100.0

The Transfer of Control From AHS to Driver

Questions 10 through 13 determined the drivers' attitudes about the transfer of control from the automated system to the driver—their responses are presented in table 9. The responses to question 10 indicate that drivers found the transfer method with which they regained control of steering and speed at the same time to be very good. The mean response to question 11, which was scored either zero or one, indicates that one of the six drivers would have preferred to have regained control of the car in some other way. Each driver responded identically both times that the questionnaire was completed. The average response to question 12 indicates that drivers felt that they had excellent control of their cars immediately after leaving the automated lane. The responses obtained for question 13 show that the commuters felt that their driving performance at the end of the post-AHS section of the drive was the same as their driving performance immediately after they regained control of the vehicle.

Attitude Toward AHS

The responses to questions 14 through 20, which dealt with the drivers' attitudes toward the AHS, are presented in table 10. The t-test comparisons found no significant differences between the first and last driving sessions for these questions. The responses indicate that drivers preferred the automated lane to the manual lanes (question 14) and unanimously found the manual lanes to be more challenging than the automated lane (question 15). The responses to

Table 9. Transfer of control from AHS to driver.

Question	First Session Mean	Last Session Mean
10. When you were given back control of the car after the period of automated travel, you took control of speed and steering at the same time. How did you feel about getting control back in this way? 0. This way was very bad 100. This way was very good	96.7	93.3
11. Would you have preferred to have been given control of the car back in some other way? 0. No 1. Yes	0.17	0.17
12. How would you describe the manner in which you controlled your car *immediately after leaving* the automated lane? 0. Very uncontrolled 100. Very controlled	88.3	73.3
13. *After leaving the automated lane*, you drove for about 10 minutes. How was your driving at the end of the 10 minutes compared to the beginning? 0. Driving at the end was very different from driving at the beginning 100. Driving at the end was the same as driving at the beginning	71.7	86.7

Table 10. Attitude toward the AHS.

Question	First Session Mean	Last Session Mean
14. Which lane did you prefer to be in? 0. Strongly preferred manual lane 100. Strongly preferred automated lane	73.3	78.3
15. Which lane was it more challenging to be in? 0. More challenging in the manual lanes 100. More challenging in the automated lane	0.0	0.0
16. How would you feel if an Automated Highway System were installed on I-380 between Iowa City and Waterloo? 0. Very unenthusiastic 100. Very enthusiastic	91.7	75.0

Table 10. Attitude toward the AHS (continued).

Question	First Session Mean	Last Session Mean
17. If an Automated Highway System were installed on I-380, what lane would you prefer driving in? 0. Would strongly prefer manual lanes 100. Would strongly prefer automated lane	90.0	83.3
18. If an Automated Highway System were installed on I-380, how would you feel about your safety? 0. Would feel much safer without an Automated Highway System 100. Would feel much safer with an Automated Highway System	79.2	74.2
19. How would the installation of an Automated Highway System affect the stress of driving? 0. Would greatly decrease stress 100. Would greatly increase stress	16.7	25.8
20. How much would you like to be told as to why the Automated Highway System is doing things with your vehicle such as accelerating, lane changing, and so on? 0. Not at all 100. A lot	63.3	51.7

question 16 indicate that drivers would feel very enthusiastic about an AHS if it were installed on a nearby interstate. The responses to question 17 show that drivers would strongly prefer the automated lane if this automated system were installed nearby. The commuters indicated that they would feel safer with an AHS than without one (question 18). They felt that the installation of an AHS would greatly decrease the stress of driving (question 19). The responses to question 20 show that drivers felt rather neutral about being informed why the AHS was making adjustments to their vehicles' speeds or changing lanes.

Cruise Control

Questions 25 and 26 dealt with cruise control. The responses to these questions are presented in table 11. Statistical analysis using t-tests between responses from the first and last sessions yielded no statistically significant results. The average responses indicate that five of the six drivers had cruise control in their vehicles and that they used it frequently.

Table 11. Cruise control.

Question	First Session Mean	Last Session Mean
25. Does your vehicle have cruise control? 0. No 1. Yes	0.83	0.83
26. How often do you use the cruise control on your vehicle? 0. Hardly ever 100. Almost always	74.0	71.0

SECTION 4. DISCUSSION

The objectives of this experiment were: to determine whether the driving behavior of the commuter is affected by repeated travel under automated control, to determine whether prior exposure to the AHS affects the subsequent driving performance of the commuter, to determine whether the time of day affects the driving behavior of the commuter, and to determine whether the driving behavior of the commuter varies from day to day. It examined the effect of commuting via the AHS, determining the effect of repeatedly traveling for extended periods under automated control to and from the same destination at the same times of day. Each of six commuters traveled to work in the morning and then returned in the afternoon on three consecutive days—Wednesday, Thursday, and Friday. Then, on the Monday following the 2-day weekend break, the commuter again traveled to and from work. Each journey was divided into three sections: in the first, the commuter controlled the simulator vehicle, driving for approximately 13.5 km (8.4 mi); in the second section, the vehicle traveled under the control of the AHS for approximately 44.7 km (27.7 mi); while in the third section, the commuter again controlled the vehicle, driving approximately 12.7 km (7.9 mi). During the time that the commuter's vehicle was in the automated lane, it traveled at a velocity of 104.7 km/h (65 mi/h)—16.1 km/h (10 mi/h) faster than the speed limit in the unautomated lanes. Also in this period, the gap between the commuter's car and the vehicle immediately ahead in the string of automated vehicles was 0.0625 s, which is much smaller than the following distance typically chosen by drivers under normal driving conditions. Driving performance data were collected before and after the commuter's vehicle had traveled under automated control. These data were compared in order to determine whether the experience of commuting via the AHS affected normal driving behavior.

AHS EFFECTS

When the pre-AHS and post-AHS driving performance data obtained in this experiment were compared, differences were found for only three measures—the steering instability, the velocity instability, and the number of velocity fluctuations per minute. Pre- vs. post-AHS differences in steering instability, velocity instability, and the number of velocity fluctuations were observed during the first 1-min segment of the post-AHS section of the sessions—showing that they were immediate AHS effects. The fact that the effects were found throughout the remaining 7 min of the post-AHS sections of the drive shows that they were also prolonged effects. The effects of the AHS on these three variables were also observed on the third day of the experiment, after the commuter had been exposed to the AHS five times, and on the fourth day of the experiment, after the commuter had experienced automated travel seven times. In addition, there were clear indications that the effect of the AHS on steering instability and velocity instability persisted from one session to the next; there was also some indication—although this was less clear than was the case with the other two variables—that the effect of the AHS on the number of velocity fluctuations persisted from one session to the next .

It might be assumed that these various effects occurred because the commuters were exposed to repeated travel under automated control. However, there are other factors that should be considered. Bloomfield, Levitan, Grant, Brown, and Hankey examined the effect of a single, extended exposure to automated travel using 48 drivers.(8) Thirty-six of these drivers traveled under automated control; the remaining 12 formed a control group. Each of the control-group drivers was in the simulator vehicle for the same length of time as the drivers who experienced travel under automated control; however, the controls drove the simulator vehicle throughout the session. Bloomfield et al. found that there was less steering instability and less velocity instability, and that there were more velocity fluctuations, after the drivers in their experimental groups had traveled under automated control for an extended period of time—a result similar to that found in the current experiment. However, they also obtained the same changes in performance for the control-group drivers. Since the changes occurred for the control-group drivers as well as the drivers in the experimental groups, Bloomfield et al. were not able to attribute the changes in performance to the experience of traveling under automated control. Instead, they concluded that the improvements in performance were either practice effects that occurred because, as the trial progressed, the driver became increasingly familiar with driving the simulator vehicle, or were the result of the driver spending time traveling in the vehicle, regardless of whether he/she was in control of the vehicle.(8)

As in the experiment conducted by Bloomfield et al., it is possible that practice or time spent traveling in the vehicle were also factors in the current, commuter experiment. They could have produced the changes in steering instability, velocity instability, and velocity fluctuations that were obtained here. The important finding in this study, as far the Automated Highway System is concerned, is that repeated exposure to automated travel in a commuter situation did not have a negative effect on the driver's lane-keeping and speed-control performance.

Bloomfield et al. did find two variables for which there were performance changes that suggested that drivers who had experienced extended periods of automated travel may have driven more aggressively after the experience—both the minimum following distance and the minimum incursion gaps decreased for the experimental-group drivers after they traveled under automated control.(8) The current experiment provides similar hints: the comparison between the minimum following distances in the pre-AHS sections and in the post-AHS sections of all eight sessions for all six drivers indicated that, after traveling under automated control, there was a tendency for the drivers to drive closer to the vehicle ahead than they had before; also, there was a suggestion that the size of the minimum incursion gaps may decrease after the driver has traveled under automated control.

Although the number of steering oscillations was not significantly affected by travel in the automated lane, the level of steering instability for the commuter followed a consistent pattern. The relationship between these two steering measures is illustrated schematically in figure 22. The diagram shown there indicates, for each of the eight commuter sessions, the line of best fit for steering and the number and amplitude of the oscillations around this line. It indicates the number of steering oscillations per minute in the pre-AHS section of the drive and in each of the seven 1-min segments of the post-AHS section. The figure shows that there were differences in the number of oscillations in some segments, e.g., there were fewer oscillations in the fourth segment of the Monday afternoon session than there were in the other segments of that session. However, as already mentioned, these differences were not statistically significant.

Figure 22 also indicates the extent of the steering instability—the greater the amplitude of the oscillations, the larger the steering instability. The figure shows that the steering instability was largest in the pre-AHS section of the first drive on Wednesday morning. It was smaller in the seven 1-min segments of the post-AHS section of this session—and it was approximately this small in all seven 1-min segments of the post-AHS sections of all eight sessions. However, when the eight pre-AHS sections are compared, it can be seen that the steering instability was relatively low in all four afternoon sessions; while in the morning on Thursday, Friday, and Monday, the steering instability was about halfway between the instability level on Wednesday morning and the level on all four afternoons.

Both the velocity instability and the number of velocity fluctuations were found to be affected by the commuter traveling under automated control. The relationship between these two speed-control measures is illustrated schematically in figure 23. The figure indicates, for all eight commuter sessions, the speed-control line of best fit along with the number and the amplitude of the fluctuations around this line. It indicates the number of velocity fluctuations per minute in the pre-AHS section of the drive and in each of the seven 1-min segments of the post-AHS section. It shows that the number of velocity fluctuations was relatively low in the pre-AHS section of the Wednesday morning session and that the number increased in the post-AHS segment of the Wednesday morning session. The figure shows a similar pattern in the remaining seven

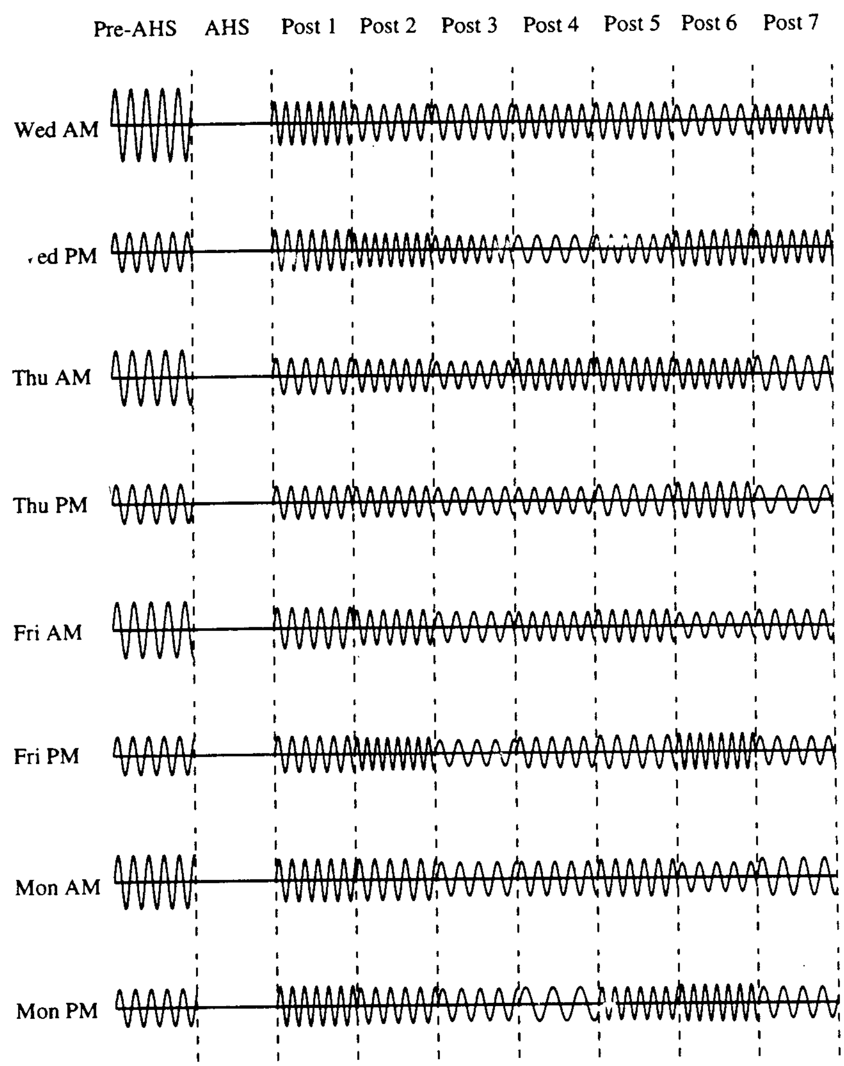

Figure 22. Relationship between steering oscillations and steering instability (each horizontal line represents the line of best fit for steering for each session).

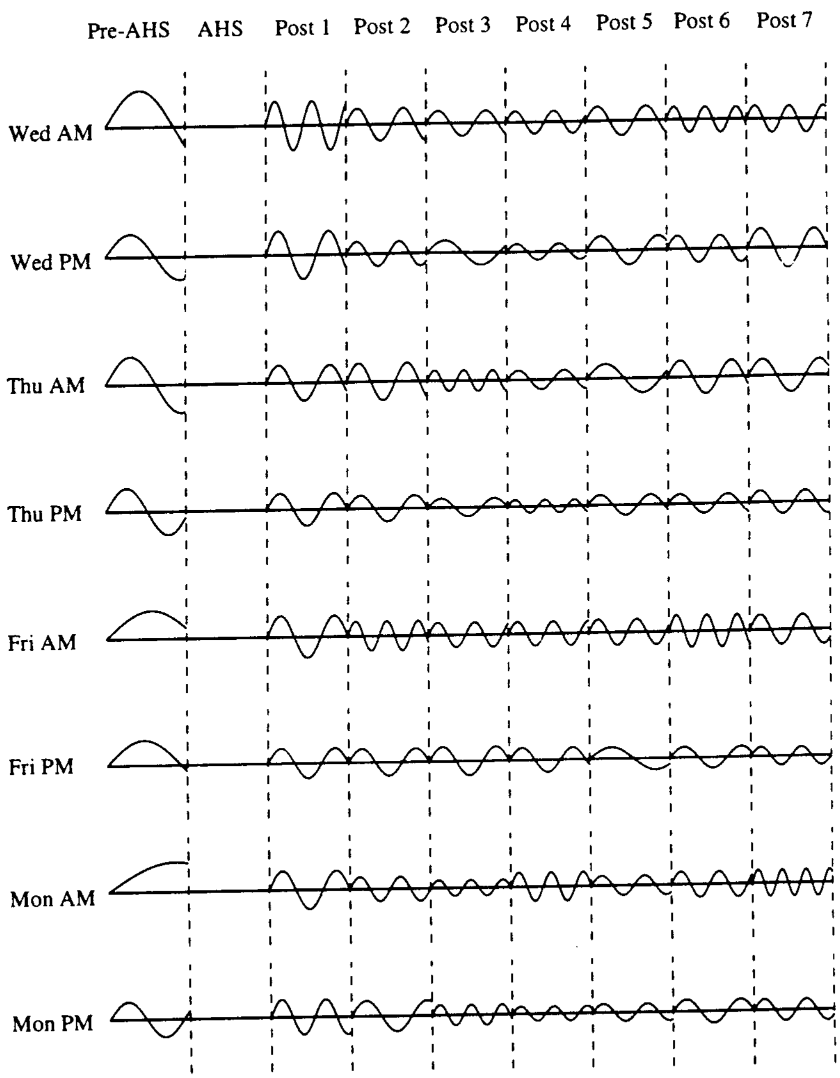

Figure 23. Relationship between velocity fluctuations and velocity instability (each horizontal line represents the line of best fit for speed control for each session).

sessions—relatively few fluctuations in the pre-AHS section of the sessions, followed by considerably more fluctuations in the post-AHS segment.

The figure also indicates the extent of the velocity instability—the greater the amplitude of the fluctuations, the larger the velocity instability. It shows that the velocity instability was largest in the pre-AHS section of the first drive on Wednesday morning. It was smaller in the seven 1-min segments of the post-AHS section of this first session—and was approximately as small in all the post-AHS segments. However, when the eight pre-AHS sections were compared, the steering instability was somewhat lower in all four afternoon sessions; while in the morning on Thursday, Friday, and Monday, it was about halfway between the instability level on Wednesday morning and the levels on all four afternoons.

The effect shown in figure 23 is in direct opposition to the results of an earlier study. Bloomfield, Christensen, and Carroll found that in order to maintain a chosen velocity, before traveling in the AHS the driver made more frequent, smaller velocity corrections; while after traveling in the AHS, the driver made less frequent, larger velocity corrections.[6] However, in that study, the drivers were exposed to the AHS for only brief periods, whereas in the current experiment, the commuters repeatedly traveled under automated control for extended periods of time.

DRIVER ACCEPTANCE OF THE AHS

In addition to exploring how the commuter's driving performance changed as a result of traveling under automated control, information was obtained about how the commuter's trust in the AHS changed with time. The average time that the commuter waited after engaging the AHS to remove both hands from the steering wheel decreased with increasing use of the automated system. It could be inferred that the commuter came to trust the AHS to take control of the vehicle.

MINIMUM GAP ACCEPTANCE

When the minimum accepted gaps for lane changes and the minimum rejected gaps for lane incursions were examined, they were found to cluster in the region between 40 m (131 ft) and 60 m (197 ft). A similar clustering of minimum accepted gaps and minimum rejected gaps was obtained by Bloomfield, Levitan, Grant, Brown, and Hankey when they investigated the effect on drivers of a single, extended exposure to automated travel.[8] The results of both the current and the previous experiment suggest that the minimum gap acceptable for a lane change is in the

40-m (131-ft) to 60-m (197-ft) region. When traveling at a speed of 88.6 km/h (55 mi/h), the midpoint of this range is equivalent to a 2.0-s gap.

CONCLUSIONS

The underlying motivation for the series of studies in which drivers traveled under automated control was to determine whether driving performance would deteriorate with increasing exposure. The study by Bloomfield, Christensen, and Carroll suggested that this might be the case.[6] After further investigation, with much longer exposure to the AHS, the results were mixed. It is arguable that the commuter's lane-keeping and speed-control performance improved. After increased exposure to travel under automated control, the commuter's steering adjustments became more precise, while in controlling speed, he/she made more frequent adjustments of smaller amplitude. In contrast, after traveling under automated control, there was a tendency for the driver to reduce the minimum following distance to the vehicle ahead, and there may have been a reduction in the size of the minimum incursion gap.

APPENDIX 1. VIDEO NARRATIVE

INTRODUCTION

Before driving in the first session of this experiment, each of the six drivers who participated was shown a video tape containing introductory material and experimental instructions. The text of the narrative used in this video is presented below.

[A. Introducing the AHS]

Passage A.1: The study in which you are about to participate is part of an on-going investigation of Automated Highway Systems. We are conducting the investigation for the FHWA, the Federal Highway Administration. The FHWA is responsible for safety and travel effectiveness on our highways. In this investigation, the FHWA is trying to determine how to design an Automated Highway System in order to reduce congestion and to increase highway safety. We are conducting a series of studies using the Iowa Driving Simulator. We will explore how an Automated Highway System might work, and how well drivers would handle their vehicles in such a system. The data provided by you, and others, will aid us in making accurate and responsible recommendations about how to design and operate the Automated Highway System. This is a test of the Automated Highway System, not a test of you or your driving skills. We will maintain your privacy—your data will never be presented with your name attached.

Passage A.2: In this study, we are interested in whether the Automated Highway System might help a driver who has to travel to work every day by car. We will ask you to drive in the simulator vehicle as if you were going to work in the morning and returning home at night for the next 4 days—that is, today, tomorrow, and on Friday of this week; and then on Monday of next week.

Passage A.3: The Automated Highway System could be designed in a number of ways. The version that you will drive in today and in the next few days, has been installed on a freeway with three lanes in each direction. In this freeway, the left-most lane is reserved for automated traffic only. All the vehicles in this lane are under the control of the Automated System. They will be arranged in strings—there may be one, two, three, or four vehicles traveling together in each string. The vehicles in the automated lane will be traveling at 65 miles per hour, faster than the traffic in the other two lanes. The right and center lanes are not automated: the vehicles in them will be controlled manually by their drivers.

[A1. Practice]

Passage A.1: When you first get into the simulator today, you will be asked to drive on the freeway for 5 minutes. This is to give you a chance to get used to the car and the way that it handles before you drive to work. This will be the only time there will be a practice drive.

[B. Driving on the Freeway]

Passage B.1: At the start of your drive to work, your car will be parked on a freeway entrance ramp. You will drive from the entrance ramp into the right lane, and then, for about 10 minutes, you will drive on the freeway.

Passage B.2: You will be able to drive in the right lane and the center lane, but not in the left lane—that is reserved for automated vehicles. If you start to move into the left lane, you will hear the following warning:
["You've entered the left lane.
You're not authorized to be in the left lane.
Return to the center lane immediately."]

Passage B.3: While you are in the right or center lanes, you will drive among vehicles that are not under automated control—these vehicles will behave in the way that traffic usually behaves on a freeway. The speed limit in the right and center lanes is 55 miles per hour.

[C. Entering the Automated Lane]

Passage C.1: Now, I will describe how you enter the automated lane and join one of the strings of automated vehicles.

Passage C.2: After driving your car for about 10 minutes, you will hear a message. If you are in the center lane, the message will be:
["Please remain in the center lane and wait for further instructions."]

Passage C.3: When you hear this message, you should remain in the center lane. You will soon hear further instructions.

Passage C.4: If, at the end of the 10 minutes, you are not in the center lane, but are in the right lane instead, you will hear this message:
["Please move to the center lane and, when you get there, wait for further instructions."]

Passage C.5: You should move to the center lane as soon as it is safe to do so.

Passage C.6: After you have been in the center lane a few moments, you will hear the following message:
["To engage the automated system, push the *On* button now."]

Passage C.7: When you push the *On* button, you will hear this message:
["Welcome to the Automated Highway System. Your vehicle is now controlled by the automated system. You will enter the automated lane in a moment."]

Passage C.8: The Automated System will take control. It will keep your car in the center lane, controlling your speed and steering, while it waits for a suitable gap in the automated lane. When it finds a suitable gap between two strings of automated vehicles, the System will move your car into the automated lane. Then, it will increase your speed gradually, until the gap between your car and the string of vehicles ahead narrows and you become the last vehicle in that string.

Passage C.9: Let me review the entry procedure. You will be driving in the right or center lane. If you are in the right lane, you will be asked to move to the center lane—if you are already in the center lane, you will be asked to stay there. After a few moments, you will be asked to press the *On* button to let the system know that you are ready to enter the automated lane. When you press the *On* button, you will hear a message informing you that the system has taken control of your car. It will move you from the center lane to the automated lane, and increase the speed of your car until you join the string of automated vehicles ahead of you.

[D. Traveling in the Automated Lane]

Passage D.1: For the next 25 minutes, the Automated Highway System will move you along rapidly in the automated lane, steering your car and controlling its speed automatically.

[E. Leaving the Automated Lane]

Passage E.1: After you have traveled in the automated lane for about 25 minutes, you will hear a message informing you that you are about to leave the automated lane. This is what you will hear:
["You will leave the automated lane in 30 seconds. Once in the center lane, you will be asked to resume control of your vehicle."]

Passage E.2: The Automated System will slow your car down to 55 miles an hour. It will continue to control your car as it moves you into the center lane. Then, you will hear the following message:
["To regain control of the vehicle, put your hands on the steering wheel and press the accelerator or brake pedal."]

Passage E.3: You will not be able to take control of your car until you have heard this message. But when you have heard the message, you should take control as soon as you can. To take control, you must first hold the steering wheel, then press either the accelerator or the brake pedal. When you have done this, the System will transfer control of the car back to you, and you will hear the following message:
["You now have complete control of your vehicle."]

Passage E.4: Once you have complete control of your car, you will be able to drive in the right lane and the center lane, but not in the left lane—that will still be reserved for automated vehicles.

Passage E.5: Let me review the procedure for regaining control of your car. You will hear the message saying you are about to leave the automated lane. The Automated System will reduce the speed of your car and move it to the center lane. You will hear a second message telling you to take control of your car by holding the steering wheel and pressing the accelerator or the brake pedal. After doing this, you will hear a message confirming that you have control of your car.

Passage E.6: You will then drive in the center and right lanes of the freeway until the end of the drive. As you get near the end of your drive to work, you will hear this message:
["In 30 seconds you will reach your destination. You should move into the right lane and leave the freeway at the next exit."]

Passage E.7: When you hear this message, you should prepare to leave the freeway. If you are in the center lane, you should move into the right lane as soon as it is safe to do so. And if you are in the right lane when you hear the message, you should remain in it, and leave the freeway at your exit.

APPENDIX 2. MAP OF THE VISUAL DATABASE AND STRIP-MAP GUIDE FOR THE DRIVER

Each commuter drove a fixed-distance route starting at Exit 7 (County Rd E) heading counter-clockwise to Exit 27 (County Rd V) in the morning, and driving from Exit 27 (County Rd V) heading clockwise to Exit 7 (County Rd E) in the evening. This emulated a commute to and from work each morning and evening. Figures 24 and 25 show the actual route traveled by the commuter in the morning and afternoon. Each commuter was aware of the upcoming exits via the two strip maps depicted in figures 26 and 27.

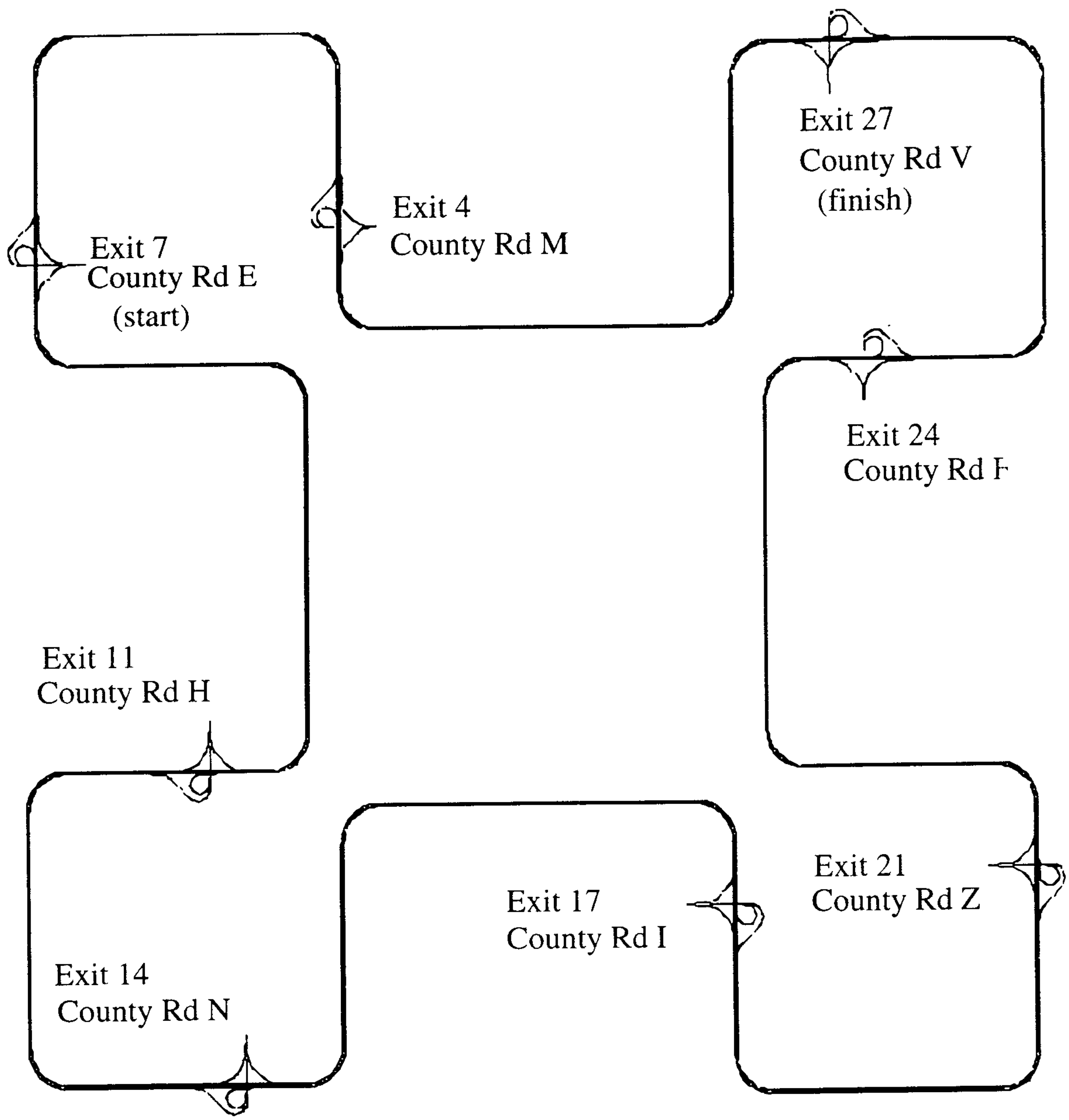

Figure 24. Map of route driven in the morning commute.

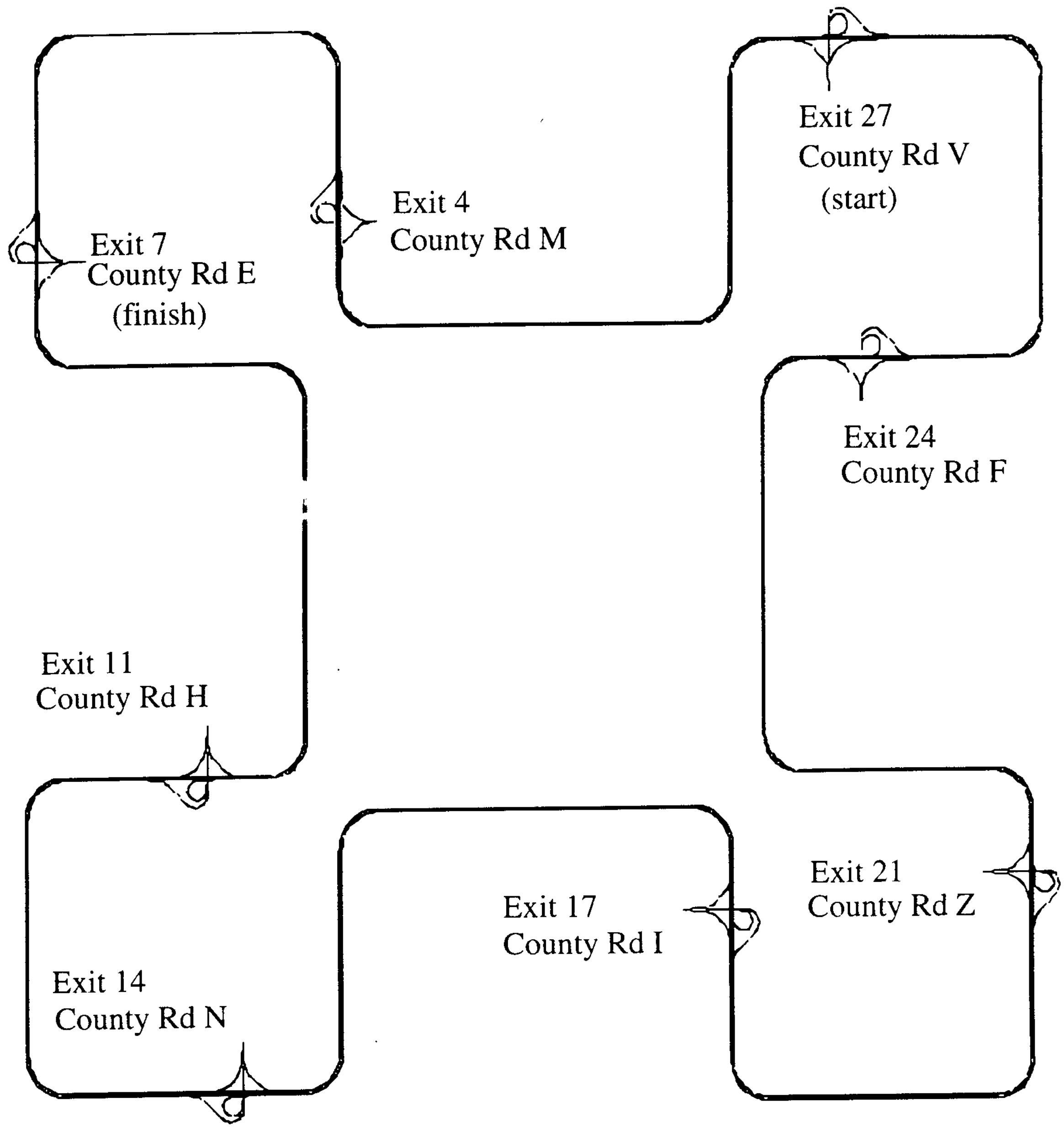

Figure 25. Map of route driven in the evening commute.

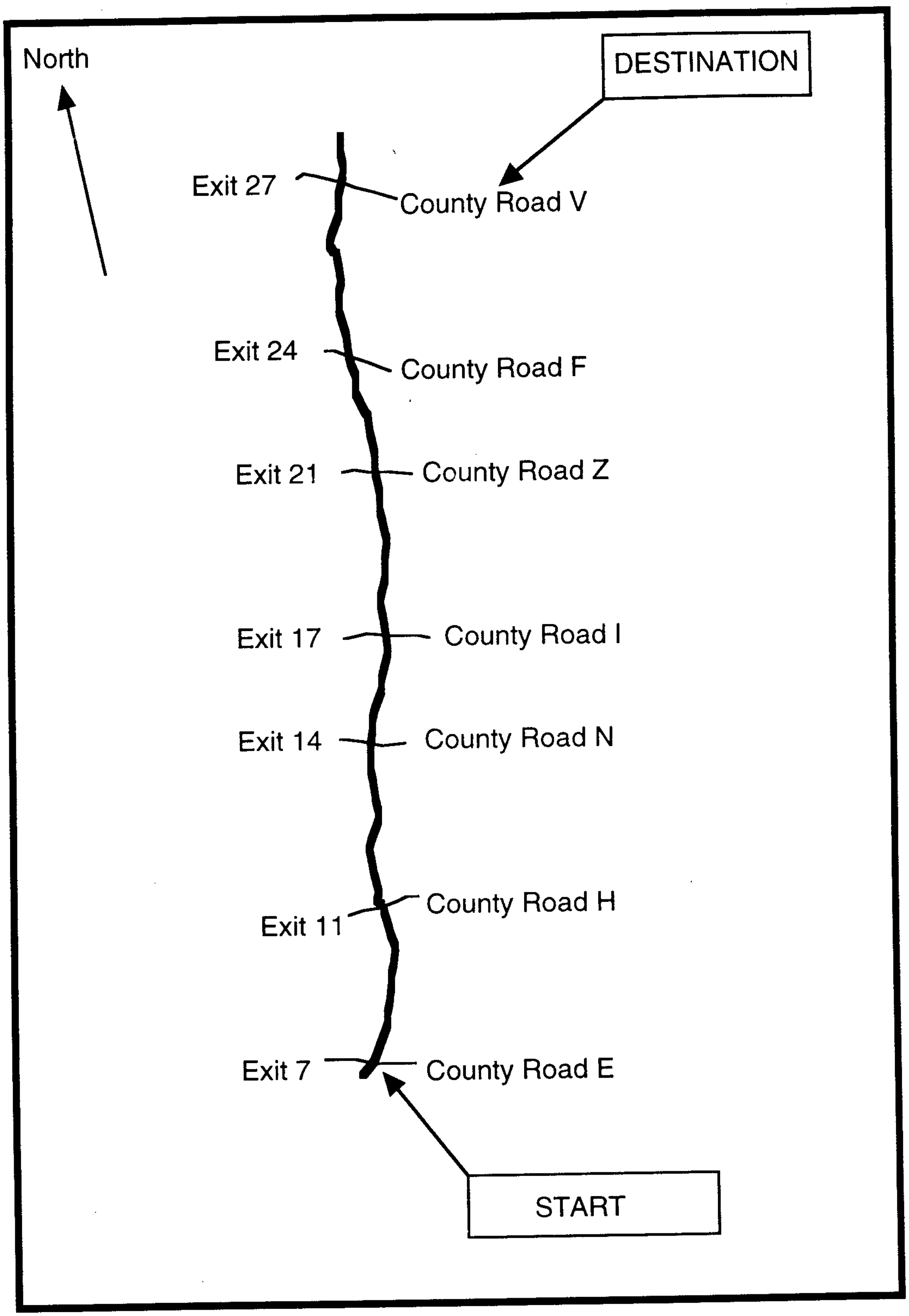

Figure 26. Strip map of route given to drivers for the morning drive.

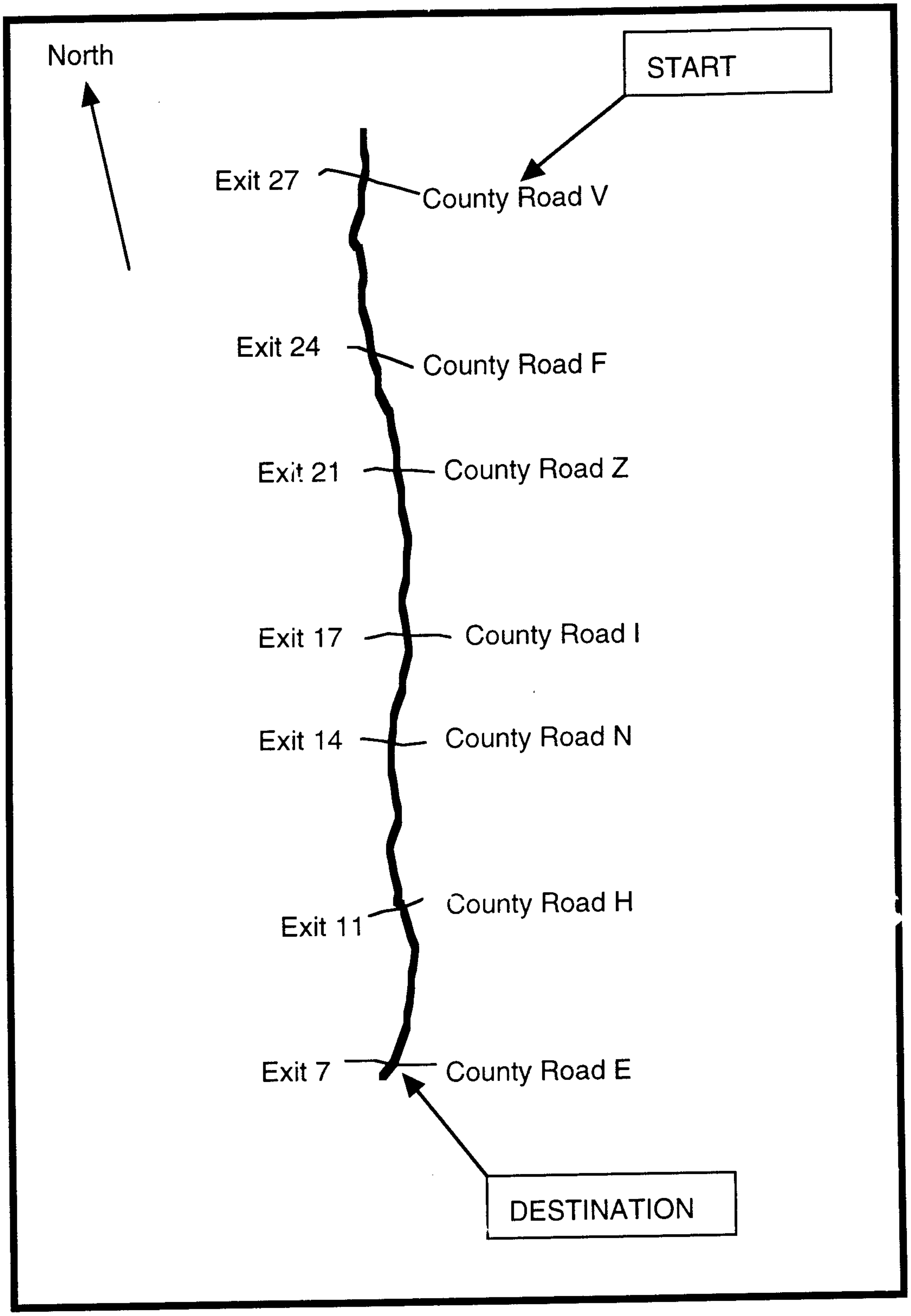

Figure 27. Strip map of route given to drivers for the afternoon drive.

APPENDIX 3. QUESTIONNAIRE

The following questionnaire deals with certain aspects of the driving simulator, the commuter study that the participants took part in, and the Automated Highway System. The same questionnaire was administered at the end of day 1, session 1, and day 4, session 2.

Instructions

The following series of questions deals with the driving simulator, the experiment that you just took part in, and the Automated Highway System. For most of the questions, you will be asked to provide a rating from 0 to 100. The meanings of the two endpoints of the scale are provided for each question. Your answer can be any whole number between 0 and 100; do not use fractions or decimals. A space is provided for you to write your answer in.

Example:

Question	Scale	Your Rating
How would you rate the importance of air bags in driver safety?	0 = Very unimportant 100 = Very important	________

If you think that air bags are pretty important in driver safety, you would provide a rating of over 50; the more important you think they are, the closer your rating would be to 100. If you think that air bags are not too important, you would provide a rating of less than 50; the more *un*important you think they are, the closer your rating would be to 0.

Questions

Question	Scale	Your Rating
1. How much did you enjoy driving the simulator?	0 = Not at all 100 = A lot	________
2. How did driving in the simulator compare to driving in your car?	0 = Very different 100 = Very similar	________
3. How realistic was the view out of the windshield in the simulator?	0 = Very artificial 100 = Very realistic	________
4. How realistic were the sounds in the simulator?	0 = Very artificial 100 = Very realistic	________

Question	Scale	Your Rating
5. How realistic was the vehicle motion in the simulator?	0 = Very artificial 100 = Very realistic	________
6. While driving the simulator, how did you feel?	0 = Did not feel well 100 = Felt fine	________
7. In this study, when your car was under automatic control, how did you feel about the speed at which you traveled?	0 = Would have preferred to go much slower 100 = Would have preferred to go much faster	________
8. In this study, when your car was under automatic control, how did you feel about the separation distance between you and the car ahead?	0 = Would have preferred a much longer separation 100 = Would have preferred a much shorter separation	________
9. How understandable was the message saying that you should take control of your car ("To regain control of the vehicle, put your hands on the steering wheel and press the accelerator or brake")?	0 = Very hard to understand 100 = Very easy to understand	________
10. When you were given back control of the car after the period of automated travel, you took control of speed and steering at the same time. How did you feel about getting control back in this way?	0 = This way was very bad 100 = This way was very good	________

11. Would you have preferred to have been given control of the car back in some other way?

- ❑ Yes (Please explain below.)
- ❑ No

____

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____

____

Question	**Scale**	**Your Rating**
12. How would you describe the manner in which you controlled your car *immediately after leaving* the automated lane?	0 = Very uncontrolled 100 = Very controlled	________
13. *After leaving the automated lane,* you drove for about 10 minutes. How was your driving at the end of the 10 minutes compared to the beginning?	0 = Driving at the end was very different from driving at the beginning 100 = Driving at the end was the same as driving at the beginning	________
14. Which lane did you prefer to be in?	0 = Strongly preferred manual lane 100 = Strongly preferred automated lane	________
15. Which lane was it more challenging to be in?	0 = More challenging in the manual lanes 100 = More challenging in the automated lane	________
16. How would you feel if an Automated Highway System were installed on I-380 between Iowa City and Waterloo?	0 = Very unenthusiastic 100 = Very enthusiastic	________

Question	Scale	Your Rating
17. If an Automated Highway System were installed on I-380, what lane would you prefer driving in?	0 = Would strongly prefer manual lanes 100 = Would strongly prefer automated lane	________
18. If an Automated Highway System were installed on I-380, how would you feel about your safety?	0 = Would feel much safer without an Automated Highway System 100 = Would feel much safer with an Automated Highway System	________
19. How would the installation of an Automated Highway System affect the stress of driving?	0 = Would greatly decrease stress 100 = Would greatly increase stress	________
20. How much would you like to be told as to why the Automated Highway System is doing things with your vehicle, such as accelerating, lane changing, and so on?	0 = Not at all 100 = A lot	________

21. What kinds of information would you find useful during an actual trip on an Automated Highway System?

____

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____

22. What kinds of information would you like to be able to provide *to* the Automated Highway System? (For example, if there is some disturbance on the road ahead, would you like to be able to tell that to the System?)

____

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____

23. Do you have any comments on the Automated Highway System?

____

____

____

____

____

24. What type of vehicle do you *usually* drive? Please check one and indicate the make and year.

	Make	Year
❑ Car	________	______
❑ Van	________	______
❑ Truck	________	______
❑ Motorcycle	________	______
❑ Other (specify) ________	________	______

25. Does your vehicle have cruise control?

❑ Yes (Please go to question 26.)

❑ No (Stop. You have completed the questionnaire.)

Question	Scale	Your Rating
26. How often do you use the cruise control on your vehicle?	0 = Hardly ever 100 = Almost always	______

APPENDIX 4. DRIVING MEASURES

Using ideas derived from regression analysis, Bloomfield and Carroll developed a set of lane-keeping and speed-control measures.(17) They showed how to determine two linear equations. The first of these is a lane-keeping equation that represents the line of best fit for a series of points that indicate the offset of the center of a vehicle from the center of the lane, as the vehicle travels along the freeway. The second is a speed-control equation that Bloomfield and Carroll called a velocity maintenance equation, which represents the line of best fit for a second series of points that indicate the velocity of a vehicle as it travels along the freeway.

The lane-keeping equation describes the position of the vehicle relative to the center of the lane at a given time. It indicates how far the vehicle is offset to the left or right of the centerline of the lane. It also shows whether the vehicle is veering to the left or to the right or is traveling parallel to the lane throughout the series of points. The variability of the actual track of the vehicle around this line of best fit is used, along with the number of crossings of the direction of travel (or line of best fit), to indicate the stability of the driver in maintaining the track of the vehicle. In the current experiment, data were collected at a rate of 30 Hz so that as the vehicle traveled along a straight road segment, the track of the vehicle could be used to determine the position of the center of the vehicle relative to a series of perpendicular lines drawn at 1/30-s intervals. Bloomfield and Carroll assume that the series of positions could be described by the following linear equation:

$$p = a_p + b_p x \qquad (1)$$

where:

- p is the point (representing the center of the driver's vehicle) at which the line of best fit crosses the perpendicular across the lane after the vehicle has traveled distance x.
- x is the distance traveled in the lane by the vehicle.
- a_p is the point at which the line of best fit crosses the perpendicular at the start of the straight road segment. If a_p equals zero, it crosses the perpendicular line at its center. If a_p is positive, then the line of best fit starts to the left of the centerline (assuming one is looking in the direction of travel); and if a_p is negative, it starts to the right of the centerline.
- b_p is the gradient of the line. If b_p equals zero, the vehicle is traveling along the centerline of the lane or parallel to it; if b_p is positive, the vehicle is moving from the right of the

lane to the left (assuming one is looking in the direction of travel); and if b_p is negative, the vehicle is moving from the left to the right of the lane.

The series of positions of the center of the vehicle is unlikely to fall exactly on a straight line. However, since in comparison to the 3.66-m (12-ft) width of the lane, the vehicle will travel along what is, relatively speaking, a very long, straight road segment, it is not unreasonable to assume that the series of positions can be described by a linear equation. Since the equation suggested by Bloomfield and Carroll is a linear regression equation, the line of best fit of this equation can be calculated using the method of least squares. Using the method of least squares—which minimizes the error in predicting p from x—a_p and b_p are calculated as follows:

$$b_p = \frac{\sum xp - \frac{(\sum x)(\sum p)}{n}}{\sum x^2 - \frac{(\sum x)^2}{n}} \tag{2}$$

$$a_p = \frac{1}{n}\left(\sum p - b_p \sum x\right), \tag{3}$$

where n is the number of data points obtained while the vehicle traveled distance x, and b_p, p, *and* a_p are as defined following equation 1.

In addition, the variability in b_p —the residual standard deviation—can be used as an estimate of I_p , the steering instability. I_p provides an estimate of the variability in steering that occurs when the driver is attempting to maintain a straight course along the line of best fit. It is given by the equation:

$$I_p = \sqrt{\left[\sum p^2 - \frac{(\sum p)^2}{n} - \frac{\left\{\sum xp - \frac{(\sum x)(\sum p)}{n}\right\}^2}{\sum x^2 - \frac{(\sum x)^2}{n}}\right] \div (n-2)} \tag{4}$$

Equations 1 and 2 define the position of a vehicle in a straight road segment; equation 3 gives information on steering drift across the lane (if there is any); and equation 4—along with the number of crossings of the direction of travel (or steering oscillations)—provides a measure of the smoothness or stability of the ride.

If there was to be a radical change in the direction of the vehicle—and the most radical change that could occur while the vehicle remains in the lane would occur if, for example, the vehicle first veered from the extreme right of the lane to the extreme left, then changed direction and veered from the extreme left back to the extreme right of the lane—then the measures would indicate the radical change since the steering instability would be relatively large, but there would be only two steering oscillations.

The current experiment explored the driving performance of drivers while they were driving on straight and curved segments of expressway, both before and after they had experienced traveling under automated control. Bloomfield and Carroll also demonstrated that it is possible to use this linear equation to describe the track of a vehicle traveling around a horizontal curve, as long as the position of the vehicle in the lane is determined relative to the cross section of the lane.(17) When the road is curved and the position of the vehicle in the lane is determined relative to the cross section of the lane, then at each moment, the position of the vehicle will be expressed relative to a line that is perpendicular to the tangent of the curve. In the current experiment, data were collected at a rate of 30 Hz. As a result, around every curve there was a series of tangents at $^1/_{30}$-s intervals—each with a cross-sectional line that was perpendicular to it. On the cross-sectional lines, a series of points that indicated a series of lane positions was recorded. When these cross-sectional lines were considered together—and the wedge-shaped slivers of the curve between them were ignored—the curve that the vehicle traveled around could be treated mathematically as a straight line, and a linear equation could be used to describe the track of the vehicle.

A set of equations similar to those used to describe lane-keeping performance can be used to describe the driver's ability to maintain the velocity of the vehicle. In this case, there are two velocity maintenance measures. The first is a measure of the stability of velocity maintenance (analyzing velocity at any given instant). The other indicates any tendency for the velocity to drift higher or lower. This is determined by the number of velocity reversals across the line of best fit (or velocity maintenance line). The equations used in this case differ in that p, a_p, b_p, and I_p in equations 1, 2, 3, and 4 are replaced by v, a_v, b_v, and I_v, respectively, in equations 5, 6, 7, and 8. Equations 5, 6, and 7 provide a description of how well the driver maintains velocity, equation 8 is a measure of smoothness or stability in maintaining velocity. These equations are presented below:

$$v = a_v + b_v x \tag{5}$$

$$b_v = \frac{\sum xv - \frac{(\sum x)(\sum v)}{n}}{\sum x^2 - \frac{(\sum x)^2}{n}} \tag{6}$$

$$a_v = \frac{1}{n}\left(\sum v - b_v \sum x\right) \tag{7}$$

$$I_v = \sqrt{\left[\sum v^2 - \frac{(\sum v)^2}{n} - \frac{\left\{\sum xv - \frac{(\sum x)(\sum v)}{n}\right\}^2}{\sum x^2 - \frac{(\sum x)^2}{n}}\right] \div (n-2)} \tag{8}$$

where:

- v is the velocity, indicated by the line of best fit, after the vehicle has traveled distance x.
- a_v is the point at which the line of best fit intercepts the velocity axis at the start of the straight road segment.
- b_v is the gradient of the line. If b_v equals zero, the vehicle is traveling at a constant velocity; if b_v is positive, the velocity of the vehicle is gradually increasing; and if b_v is negative, velocity is gradually decreasing.
- n is the number of data points obtained while the vehicle traveled distance x.
- I_v is the instability in velocity maintenance. It is an estimate of the extent of the velocity fluctuations that occur when the driver is attempting to maintain a chosen velocity.

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